Chapter 8
Treatment of Low-Level Radioactive Waste

8-1. Introduction

This section provides descriptive information on treatment techniques for LLRW. The processes described must be adjusted for site-specific conditions to ensure appropriate technology application. Because waste treatment must consider so many materials and conditions, good reliable treatability data are essential. Final designs must be based upon field data ascertained from bench and/or pilot plant scale testing of specific waste streams. Many of the methods discussed in this chapter are also relevant to mixed waste, Chapter 12, and vice versa. Since radioactivity cannot be reduced, except by time, the primary objectives are usually to reduce waste mobility and the risk of intrusion. The usual methods are transfer, concentration, confinement, and isolation.

8-2. Volume Reduction of Solids

a. Compaction.

(1) General description. Compaction is performed in order to reduce the waste volume. Waste being sent to the Envirocare of Utah site does not need to be compacted. Compaction also concentrates the radionuclides, which may then add to the hazard, as well as the transportation and disposal costs, of the waste. It should first be determined whether compaction is beneficial to the treatment and disposal scheme of each waste.

(2) Regulatory oversight. While the treatment of LLRW by compaction must be carried out under an NRC or Agreement State license, no specific regulations exist that require the proapproval of a compactor design by a federal or state regulatory agency or that provide specific guidance for compactor design and operation. Operators of compactors for processing low-level radioactive waste are required by 10 CFR 20 to maintain exposures of employees and public to levels that are as low as reasonably achievable (ALARA). Releases of airborne radioactivity are regulated under the Clean Air Act radionuclide provisions and Appendix B of 10 CFR 20. Other individual state and local permits may also be required. Compactors are also required to meet OSHA requirements established in 29 CFR 1910 to protect operators from hazards other than radiation.

(3) Compatible and noncompatible wastes. Dry waste is sometimes categorized as either compatible or noncompatible. Plastics, paper, absorbent material, and cloth are compatible in conventional compactors. Metal pipe, valves, conduit, wood, and other like items are compatible in supercompactors. The following describe major types of compactors:

(4) Drum compactors. The most widely used compactor for LLRW is the drum compactor shown in Figure 8-1. This unit consists of an electrically driven pump, a hydraulic cylinder to which the platen is attached, and a ventilation system comprised of a prefilter, an HEPA (high-efficiency particulate air) filter, and a fan. Drum compactors, also called conventional compactors, usually employ 10 to 30 tons (45 to 133 N) of force for compaction. Conventional compactors require sorting to remove objects resistant to pressures of approximately 30 psi (207 kPa).

(5) Box compactors. A box compactor is similar to a drum compactor except that the waste is compacted into boxes. As shown in Figure 8-2, the design of a box compactor consists of a compactor/ram, hydraulic unit, filter system, and controls. The compactor/ram unit is completely enclosed in steel to provide protection from flying particles and radiation shielding, and to control airborne particulate. Box compactors can accept larger objects and utilize space more efficiently than drum compactors. Box compactors use forces of approximately 250 tons (1, 112 N) for compaction. Box compactors allow noncompatible material to be placed into the bottom of a disposal package with compatibles on top.

(6) Supercompactors. Essentially, supercompactors are extensions of conventional and box compactors with more powerful hydraulic drivers. All supercompactors are designed with an enclosure and equipped with air filtration systems to restrict the release of airborne contaminants. Supercompactors are available as either fixed-base or mobile units. Figure 8-3 shows the Westinghouse/Hittman mobile unit. The unit employs a 1,000-ton (4,448-N) hydraulically operated compactor mounted in a 40-ft (12-m) trailer. Supercompactors are able to compact some materials previously considered noncompatible by using forces greater than 1,000 tons (4,448 N). The supercompactor operated by Scientific Ecology Group, Inc. (SEG) has a compaction force of 5,000 tons (22,000 N). It will seldom be economical to send waste to a supercompactor if it has already been compacted to 50 to 55 lb/ft^3 (800 to 880 kg/m^3). A supercompactor will remove liquid from the waste. Supercompaction will compact otherwise noncompatible material such as wood, conduit, small diameter piping,
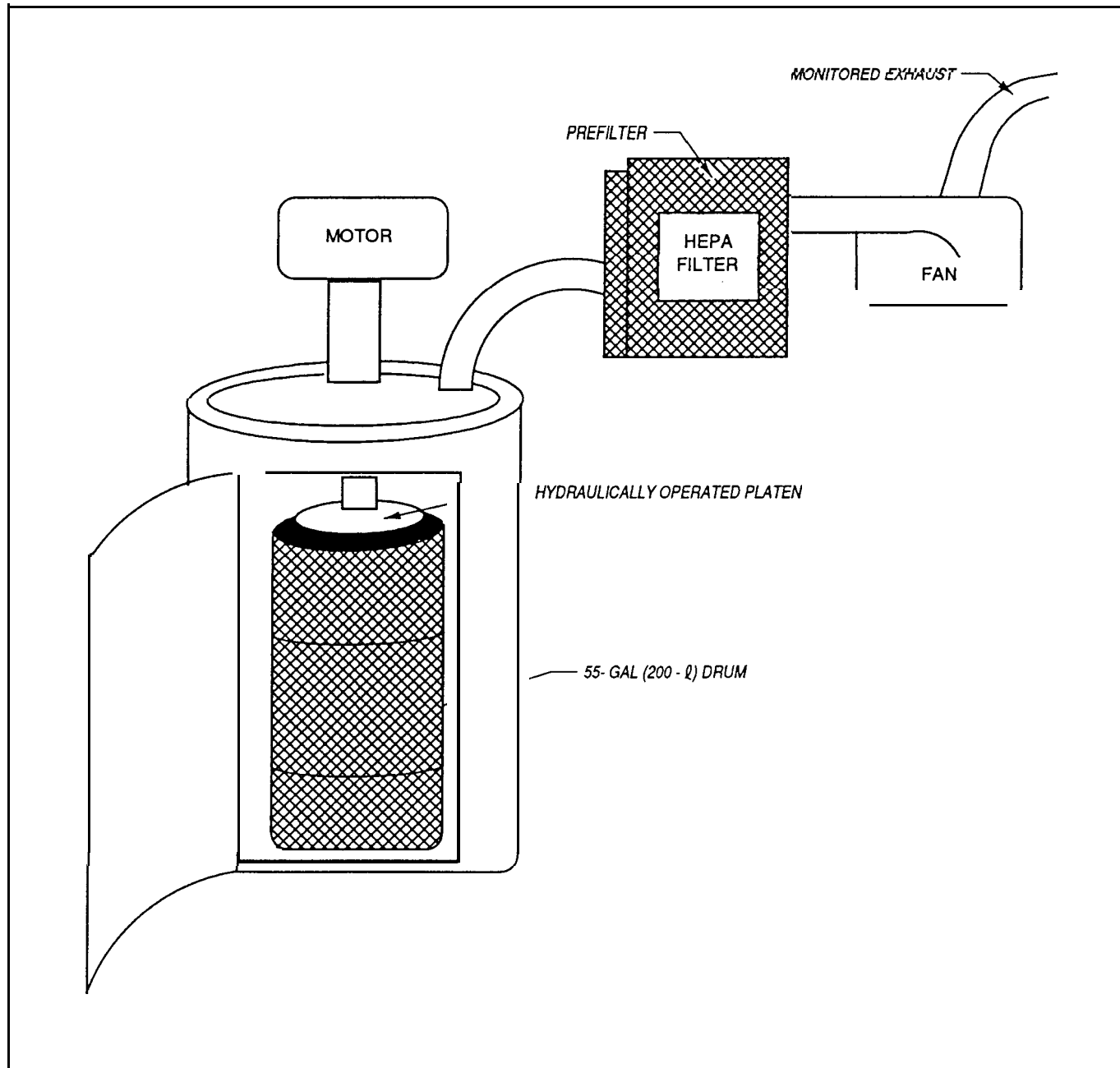
Figure *8-1.* Conventional compactor (Copyright © 1991. Electric Power Research Institute. EPRI NP-7386-VI. *Radwaste Desk Reference. Volume 1: Dry Active Waste.* Reprinted with per mission.)

small pumps, and valves. An example of a super-compactor is the Defense Consolidation Facility located in Barnwell, SC. The Corps and other members of the Services had used this facility to compact LLRW- contarninated items including very large equipment, prior to disposal at Barnwell, SC. Advantages and disadvantages of these compactors are compared in Table 8-1.

(7) costs. In the power industry, dry waste is usually compacted in 55-gal (200-1) steel drums (7.5 ft^3 or 0.2 m^3 burial volume) or in metal boxes (98 ft^3 or 2.8 m^3 burial volume). When choosing which type of compactor, the cost savings from volume reduction, labor, operating and maintenance costs of the compactor, and the volume of compatible waste enter into the
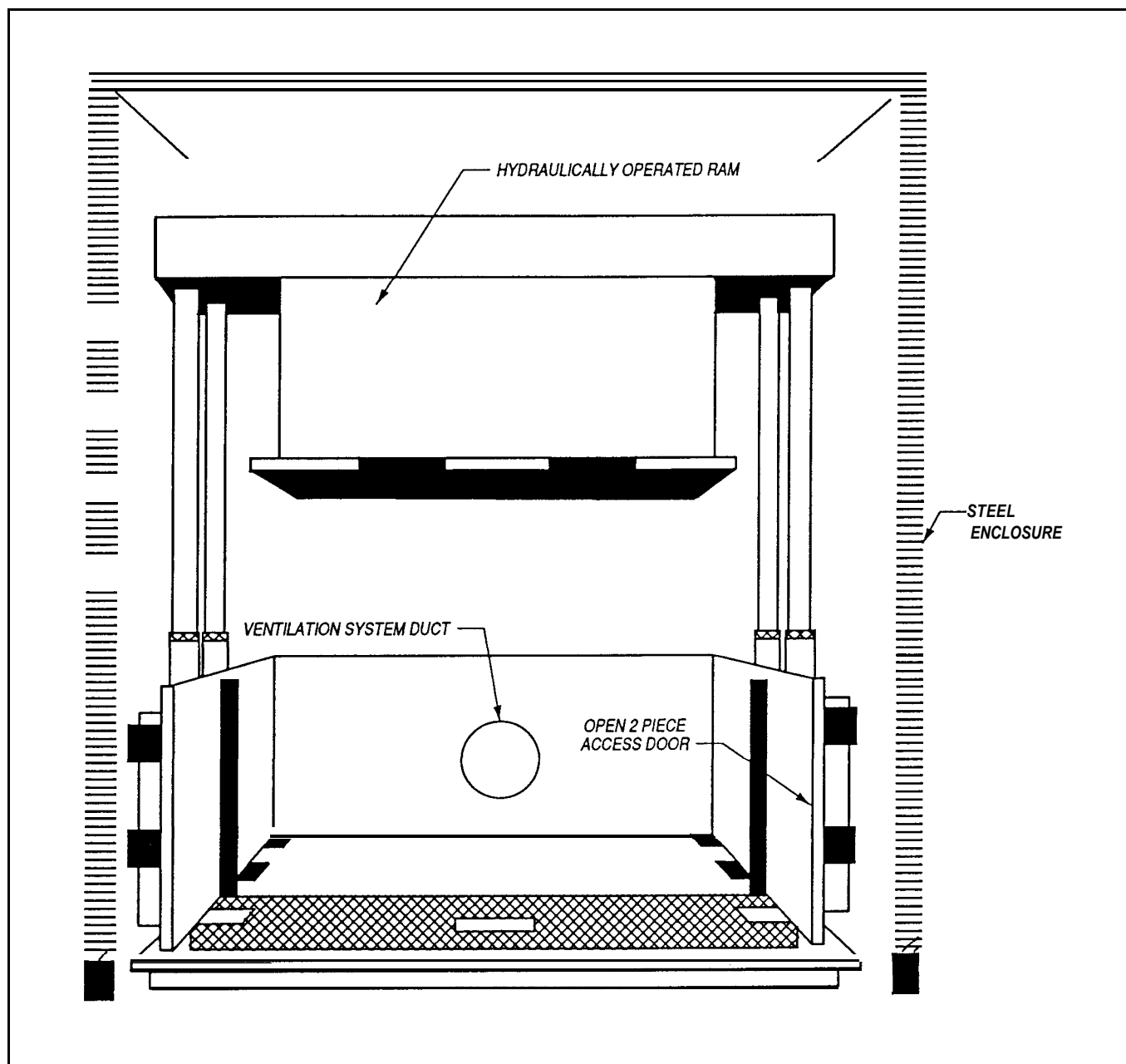
Figure *8-2.* Typical box compactor (Copyright © 1991. Electric Power Research Institute. EPRI NP-7386-VI . *Radwaste Desk Reference, Volume 1: Dry Active Waste.* Reprinted with permission.)

economic comparison. A typical drum compactor will cost $25,000 - $80,000 (1991 dollars), and a box compactor will probably cost $125,000 - $250,000 (1991 dollars). Installation costs should also be included in the comparison, with box compactors using less labor than drum compactors. Installation costs for a typical 55-gal (200-1) drum are approximately $28 (1991 dollars), while the cost of installing a box is approximately $500 (1991

dollars) . A single drum compactor can easily become overloaded, so for large waste volumes the box compactor might be the only viable option.

(8) Anti-springback devices for drums. An anti-springback device holds in place material that has been compressed. The basic design and material determine its effectiveness. The most common anti-springback devices
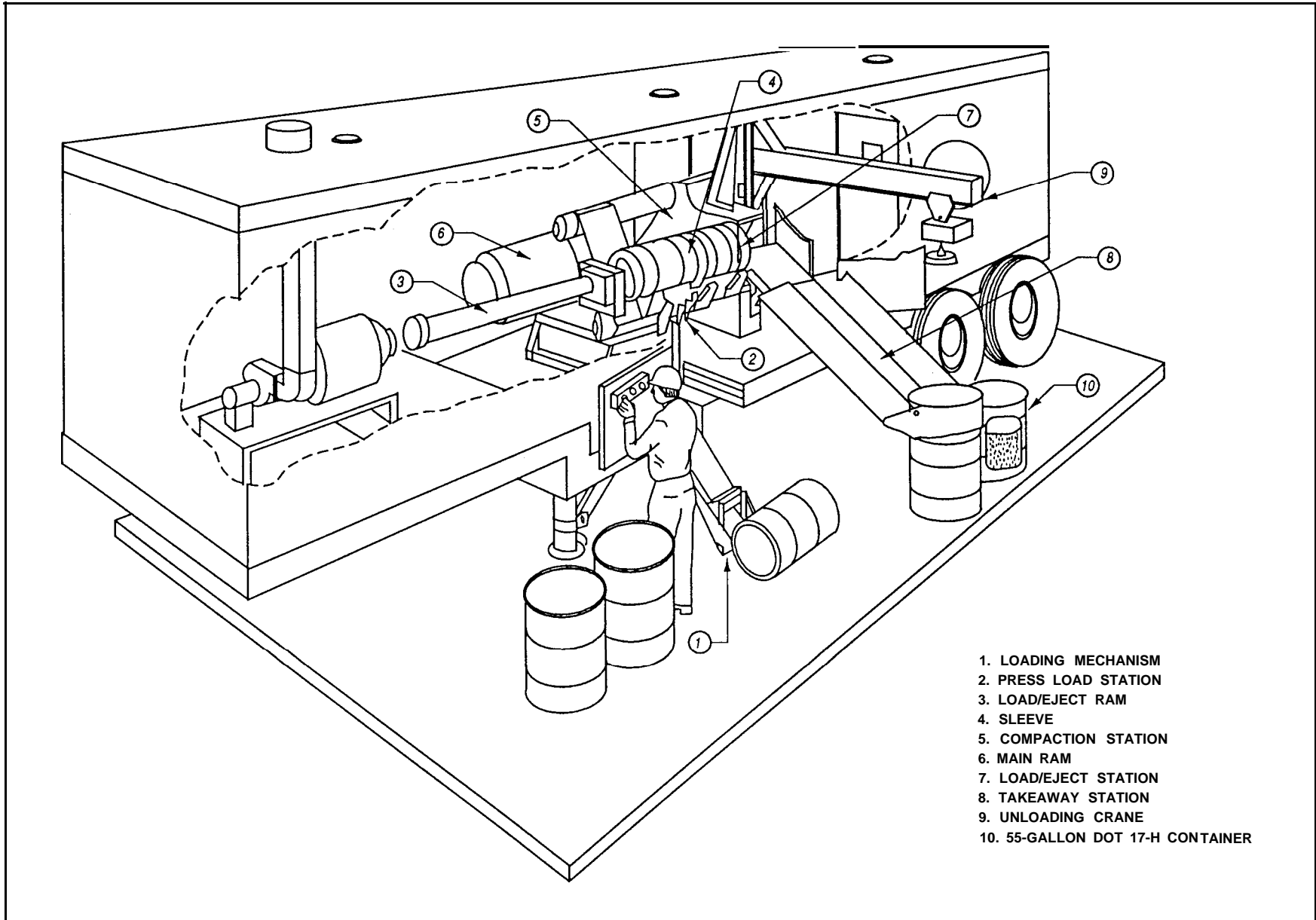
Figure 8-3. Mobile supercompactor (Copyright © 1991. Electric Power Research Institute. EPRI NP-7386-V1. *Radwaste Desk Reference, Volume 1: Dry Active Waste.* Reprinted with permission.)

1. LOADING MECHANISM
2. PRESS LOAD STATION
3. LOAD/EJECT RAM
4. SLEEVE
5. COMPACTION STATION
6. MAIN RAM
7. LOAD/EJECT STATION
8. TAKEAWAY STATION
9. UNLOADING CRANE
10. 55-GALLON DOT 17-H CONTAINER

Table 8-1
Advantages and Disadvantages of Compactors

Advantages	Disadvantages

I. Conventional compactors
• Low capital cost
• Requires only one operator
• Reduces the number of drums shipped off site, therefore reducing:
  - Transportation cost
  Burial cost
  - Paperwork required for off site disposal
• Minimal floor space required
	• Mechanical components will require periodic maintenance
	• Potential of oil leaks in the hydraulic lines
	• Requires use of an overhead crane or forklift with drum grab attachment

II. Box compactors • Large receptor opening is convenient for large pieces of waste • Large waste containers result in fewer containers to be shipped offsite and corresponding reduction in paperwork • Hydraulic unit that may require servicing can be located in a nonradioactive area, thus reducing worker exposure during maintenance activities . Containers usually contain skids and do not require pallets as do drums • Container shape more efficient for storage, transportation, and disposal	• Increased capital and individual container disposal cost • Two operators are required to place lid on waste container • Forklifts may be required to handle waste containers • Occupies more space
III. Supercompactors • Dry active wastes previously considered noncompatible are compatible, including pipes, valve bodies, and other metal products • Storage space previously occupied by wastes that were considered no longer compatible is reduced • Storage space at regional burial sites can be reduced • Relatively simple to operate	• Large capital investment • Requires large amount of floor space • Due to high compressive forces, the equipment may require more maintenance than other compactor types • Liquid waste from punctured capsules may be released during compaction

Source: DOE 1988

are cardboard disks, Teflon disks, metal disks, and box-type devices. Twenty-five to fifty percent more waste can be packaged using anti-springbacks.

(a) Cardboard disks. Cardboard disks are the simplest devices; however, they are not recommended because the cardboard cannot withstand much force. A piece of round cardboard is placed in the drum before compaction, and the drum hoops hold it.

(b) Teflon disks. A more effective device is the Teflon disk, which is a patented product of Cromwell Welding Company (Figure 8-4). The edge of the disk is angled so it can be pushed into a drum hoop by the compactor ram. By using these devices, drums can be compacted to 55 lb/ft^3 (880 kg/m^3). The Teflon disk can deform the drum by collapsing a hoop or ring. This may

occur when compacting pressures are 60,000 psi (413,000 kPa) or more. Teflon disks may also expand the diameter of a thin-walled drum and reduce the effectiveness of the anti-springback device. Usually, 16-gauge drums are used when compressing waste at high force with Teflon disks.

(c) ESSI disk. Electro-Sonics, Inc., has patented the ESSI anti-springback system (Figure 8-5). This system is a sheet metal disk with four metal clips that slide one way on threaded rods. After being pushed down by the ram, the metal disk prevents springback. Gross drum weights exceeding 500 lb (66 lb/ft^3) or 227 kg (1,056 kg/m^3) are claimed to be achieved with this system. The greatest drawback to the ESSI system is
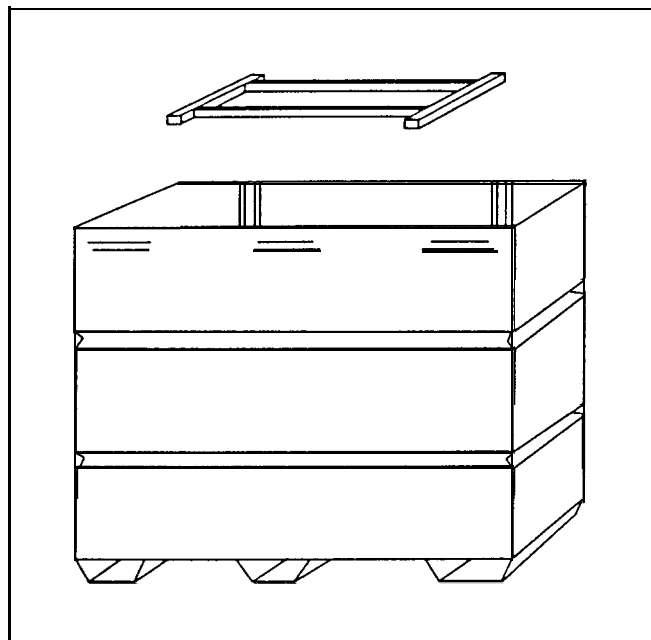
**Figure 8-6. Box type anti-springback device [Copyright ©
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(10) Maintenance. The most common problem in
compactor maintenance is filter clogging. This can be
corrected with proper prefilters and routine prefilter and
filter changes.

(11) Mixed waste. If a compactor is to be used to
treat mixed waste, it may be required to be permitted
under RCRA as a treatment facility (40 CFR 264).
Compacted mixed waste must be disposed of in accor-
dance with RCRA requirements whether or not the com-
paction facility is RCRA permitted.

b. Cutting, crushing, shredding.

(1) Cutting.   Cutting and sawing operations are
carried out mainly on large items which consist usually of
metals or plastics.   This waste has to be reduced in size
to make it fit into packaging containers or to submit it to
treatment such as incineration. The cutting is carried out
either in the dry state in cells, using remote control when
necessary and with conventional tools, or underwater.
The cutting may also be done with plasma-jets, laser
torches, or explosive fuses.

(2) Crushing. Crushing techniques may be used for
size reduction of friable solids (e. g., glass, concrete,
ceramics). Crushing increases the apparent density of the

waste.   In principle, all types of mill, grinder, and crush-
ing machines of conventional technology can be used.

(3) Shredding. Shredding reduces void space and is
particularly effective when plastics are compacted. Air,
which is trapped between the folds of bulk plastic and in
plastic bags and sleeving, takes up storage space. When
the plastic is shredded, better use is made of the waste
container space.   Recent studies show that when
compacting pressures exceed 55 lb/ft^3 (880 kg/m^3),
shredding makes little difference.

(a) High-speed shredders.   The two types of
shredders used for size reduction are high-speed
shredders and low-speed shredders.   High-speed shred-
ders include hamrnermills and flailmills.   High-speed
shredders have several disadvantages in a nuclear
environment:

- Due to their high operating speeds, they are very
  susceptible to exploding when encountering
  unshreddable materials such as steel plates.
  Therefore, waste must be thoroughly sorted.

- Harnmermill installations require daily mainte-
  nance (hardfacing and/or replacement) of the
  hammers.   Liners must also be periodically
  replaced. This level of maintenance is unaccept-
  able in the nuclear environment where workers
  would be exposed to radiation during such
  maintenance.

- In the smaller capacity range they have a limited
  open area for feeding waste material and are not
  amenable to the feeding of boxed or packaged
  wastes.

. They require considerably more horsepower than
  a comparably sized low-speed shredder.

(b) Low-speed shredders. Low-speed shredders are
generally used for LLRW applications. Batch and con-
veyor feeding can be accomplished with a low-speed
shredder. The effectiveness of the shredder depends on
the composition of waste being shredded and the desired
method of processing or disposal of the waste after
shredding.   Requirements for a shredder will vary
depending on whether the shredded waste is next com-
pacted, incinerated, or loaded directly into drums for
disposal.   Standard 55-gal (200-/) steel drums can be
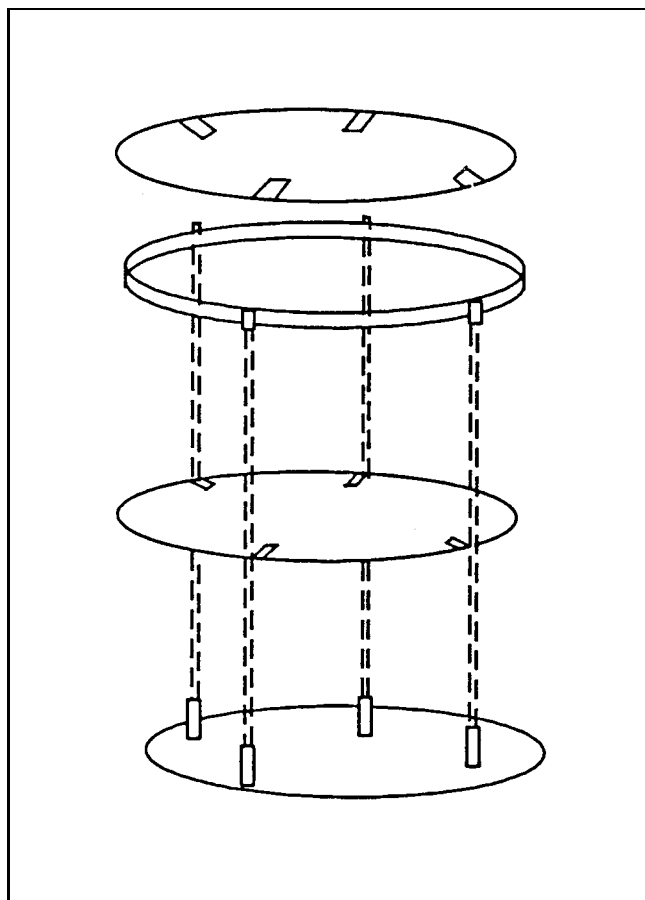easily handled in low-speed shredders.
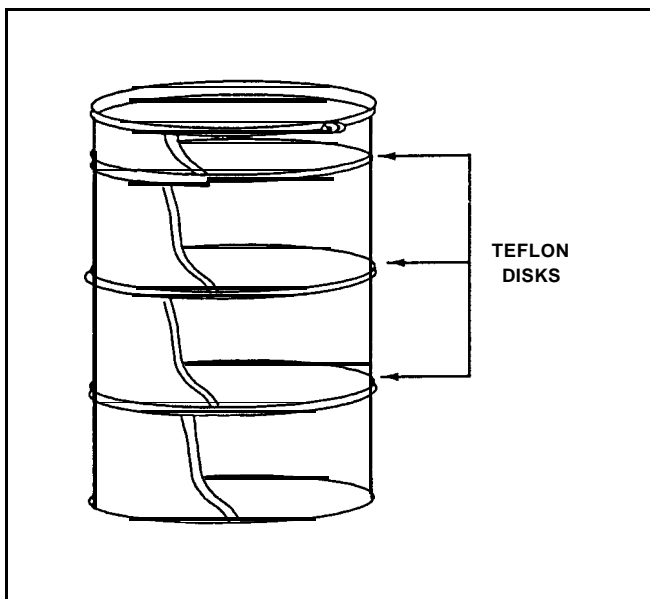
Figure 8-4. Teflon disk anti-springback device (Copyright © 1991. Electric Power Research Institute. EPRI NP-7386-V1. *Radwaste Desk Reference, Volume I: Dry Active Waste.* **Reprinted with permission.)**

that inexperienced operators sometimes misalign the disk so that it twists out of place. An extension ring, alignment fixtures, or tape markings should end this problem.

(d) Anti-springback devices for boxes. Anti-springback devices for box compactors work much the same as those for drum compactors. One device locks into the recessed or indented sides of a box (Figure 8-6). A more effective device has ribbed guides welded to the sides of the box. An anti-springback device is placed on top of the waste before compression, and the tips slide into the guides and lock under the ribs of the box. Extenders to place the anti-springback device above the top of the box save time and dose. Waste can be compacted up to 45 lb/ft^3 (720 kg/m^3) using this device.

(e) Disadvantages of anti-springback devices. No anti-springback devices used in drums prevent supercompaction. However, anti-springback devices with vertical support rods may resist compaction in some supercompactors. When they buckle in the middle, they can puncture the compacted drum or damage the compaction chamber. When used properly, vertical rod anti-springback devices are so effective that supercompaction will not be cost-effective. Anti-springback devices used in boxes can interfere with supercompaction. Vendors normally empty boxes for reuse, but box type anti-springbacks are designed to be permanent. Removing

Figure 8-5. Electro-sonic anti-springback device (Copyright © 1991. Electric Power Research Institute. EPRI NP-7386-V1. *Radwaste Desk Reference, Volume I: Dry Active Waste.* **Reprinted with permission.)**

anti-springbacks from boxes is labor-intensive, dangerous, and expensive.

(9) Ventilation. There are no specific requirements for ventilating compacting systems, although all systems should have ventilation. The most common methods for ventilating compactors include:

(a) Ventilation exhaust with HEPA filters built into the compactors.

(b) Portable exhaust ducted from the compactor or the top of the waste container.

Governing guidelines are good health physics practices, such as drawing air away from the worker toward more highly contaminated areas. These systems may require an inert gas blanket system to reduce the fire risk if pyrophoric solids are processed.

(c) Maintenance. Shredders need frequent cleaning to prevent a buildup of contamination on blades. This buildup may add to the radiation dose rate and may become airborne. It is also very important to keep stray metal parts out of shredders.

(d) Costs. Capital costs for shredders range between $135,000 and $460,000 in 1988 dollars. Total system costs vary considerably because of the effect of site-specific concerns and required ancillary equipment. Shredders are most often used in conjunction with other treatment or volume reduction technologies. Shredders can be used with mixed waste but may have to be permitted under RCRA. More detailed information concerning shredders can be found in the *Resource Manual* (DOE 1988) or from numerous vendors.

c. *Incineration.*

(1) Introduction. Incineration as a hazardous waste treatment technology is discussed in EM 1110-1-502. Major differences in using incinerator technology for LLRW involve shielding requirements, use of HEPA filters, and methods of ash disposal. Incineration is primarily a volume reduction technique. It has a secondary benefit in the destruction of hazardous organic chemicals often present in mixed waste. In all instances, incineration will produce a final product, which is ash, with a higher radionuclide concentration. This ash must be treated before disposal.

(2) Incinerable wastes. Incineration is well-suited to handle combustible solids and sludges and can also handle liquids and gases. Incineration of plastics can lead to the formation of acid gases that may require gas scrubbing equipment.

(3) Rotary kiln incineration. Rotary kiln incineration employs a rotating, inclined combustion chamber which mixes combusting materials as it rotates. Wastes are fed into the chamber at the high end, along with air and auxiliary fuel. Exhaust gases are treated and released, and ash residue is collected on the low end of the kiln.

(4) Fluidized bed incineration. In a fluidized bed incinerator, a bed of inert particles (e.g., sand) lies at the bottom of the cylindrical combustion chamber. Air is forced up through the bed and the particles are fluidized. Wastes and fuel are injected at the top of the chamber, into the fluidized mass, where the mixture combusts. The turbulent atmosphere in the chamber provides good mixing of wastes to ensure complete combustion and efficient heat transfer.

(5) Circulating bed incineration. Wastes and auxiliary fuel are introduced into the combustion chamber in a circulating bed incinerator. Air is forced up through the chamber from the bottom to promote mixing and complete combustion. Particulate and gaseous products of combustion exit from the top of the combustion chamber for treatment and disposal.

(6) Infrared incineration. In infrared incineration, waste materials are fed into the furnace on a conveyor belt, and pass through on a wire mesh belt. Heating elements provide infrared energy, oxidizing the materials. Waste gases are passed through a secondary combustion chamber; ash exits on the conveyor.

d. *Pyrolysis.*

(1) Description. This technology is capable of providing volume reduction, dispersal of gases and vapors, and the immobilization of particulate. Pyrolysis is similar to incineration but employs a lower temperature and effects thermal dissociation of the waste in the absence of oxygen. Most compounds are reduced to their elemental form and are discharged primarily as carbon monoxide and hydrogen. If the pyrolyzer design includes a molten glass reservoir, heavy metals from the waste can be trapped in the glass bed. With a large unit, the flammable gaseous effluents (CO and H_2) can be recirculated for their fuel value. Alternatively, these effluents can be recombined with oxygen and released as carbon dioxide and water.

(2) Applications. Pyrolysis has applications similar to incineration (e.g., disposal of solid long-lived radionuclides, pathological and toxic wastes, organic solvents, oils, and spent resins) but is particularly applicable to waste materials that generate toxic chemicals upon ordinary incineration or retain radionuclides in the ash since these toxic chemicals and ash would have to be vitrified and encased as a stable inert glass form.

e. *Soil washing.*

(1) Introduction. Soil washing can be performed in situ or ex situ and consists of using a dilute solvent that is selective for the contaminants to be treated. Soil washing may be effective when there is an inverse relationship between particle size and contaminant concentration. Soil washing is effective for the remediation of soils with a high content of large particle size material (>90 percent sand and gravel). After size separation, a large portion of the radioactive material may be concentrated in the

fine material, leaving a minor portion in the coarse material. The coarse material may then contain low enough amounts of radioactive material for replacement onsite. Soil washing has been successfully demonstrated on soils contaminated with strontium, cesium, technetium, radium, uranium, thorium, barium, and lead. Soil washing can also be used for mixed wastes contaminated with organics or heavy metals.

(2) Ex situ process description. The soil treatment process combines dissolution with dilute selective solvents, contaminant recovery, and solvent regeneration to provide a continuous recirculating treatment process. The solvent chemistry combines well-established carbonate recovery chemistry with a chelant and an oxidant. Countercurrent extraction is used to dissolve and recover the contaminant in the ex situ treatment process. The number of extraction stages and the contact time in the extractors is determined based on the contamination level in the soil, the physical and chemical characteristics of the soil, and the level to which the soil must be treated. Removal factors (the ratio of the contaminant level in the feed material divided by the contaminant level in the treated material) of 10 to 20 are typically achievable. The solvent is regenerated by either selective ion exchange or evaporation.

(3) In situ process description. For the in situ treatment process, the recovery process is modified to accommodate the high flow rates and the potential presence of soil fines in the recirculating solvent. For in situ applications, the soil to be treated would be flushed with dilute solvent. The solvent would be recovered by horizontal recovery wells. There will be a small fraction of soil fines in the recovered solution. Magnetic separation is used to recover the contaminant.

(4) Advantages and disadvantages. Advantages and disadvantages of soil washing are presented in Table 8-2.

(5) costs. Costs for removal and burial to the former Nevada test site were reported to be approximately $1,240/m3. Current (1994) costs are approximately $250/m^3 at Envirocare of Utah and approximately $1,600/m3 at U.S. Ecology at Richland, WA. However, costs for specific projects may differ substantially depending on volume, level of contamination, and current competition. Also, all wastes may not be accepted at all sites. Bradbury et al. (1992) estimated that the cost for soil washing would be between 20 and 50 percent of the cost to remove and bury the contaminated soil.

Table 8-2
Advantages and Disadvantages of Soil Washing

Advantages	Disadvantages
Free release of treated soil	Not a well-established treatment technology
Cleaned soil supports vegetated growth	Solvent is added to soil which may make this a hazardous waste and may create a public relations problem Significant reduction in the amount of waste for disposal
Can be performed onsite	

f. Segregation of soil according to radioactivity at Johnson Atoll. An innovative technique has been developed for removing mixed plutonium and americium contamination from the coral soil matrix at the Defense Nuclear Agency's (DNA's) Johnston Atoll site. The system used arrays of sensitive radiation detectors coupled with sophisticated computer software designed by the Eberline Instrument Corporation. The software controls the segmented gate system for removing contaminated soil from a feed supply moving on conveyor belts. Contaminated soil is diverted to either (1) a metal drum where the larger sized, "hot" (over 5,000 Bq) particles are collected, or (2) a supplementary soil-washing process where dispersed, low-level contamination is washed from the soil fraction made up of very small-sized particles. Low to intermediate levels of contamination are removed from the soil to meet the DNA criterion for unrestricted use, which is based on EPA guidelines. The innovative process has achieved a 98-percent volume reduction of contaminated soil that would otherwise require special handling and packaging for offsite.

8-3. Decontamination of Solid Surfaces and Equipment

a. Absorption.

(1) Description. Various materials may be used to absorb liquid contaminants. This method is often used to contain spills. Contaminants can rapidly penetrate surfaces, and the absorbents act to contain the contaminants and prevent such penetration. Absorbents used may be attaclay, sand, anhydrous filler, sandy loam soil, and sawdust. If possible, a clay-based material should be

used. Absorbents are also used in the packaging of LLRW in order to meet the no free-standing water requirement for disposal.

(2) Advantages and disadvantages. Advantages and disadvantages of absorption are summarized in Table 8-3.

Table 8-3
Advantages and Disadvantages of Absorption

Advantages	Disadvantages
All needed equipment can be purchased from commercial manufacturers	Additional decontamination is normally required for surface residues and the subsurface
Act quickly	
Reach capacity in 1 to 2 hr	

(3) costs. The absorbent materials and application equipment are not expensive; disposal costs may be appreciable, however, because the absorbent material is considered LLRW and must be disposed of.

b. Demolition.

(1) Description. Demolition is the total destruction of a building, structure, or piece of equipment. Demolition usually occurs in conjunction with dismantling. Specific demolition techniques include complete burndown, controlled blasting, wrecking with balls or backhoe-mounted rams, rock splitting, sawing, drilling, and crushing. The debris may be treated (possibly by incineration) and is then disposed of. The building is usually pretreated for the majority of the radioactive material before demolition, and some structures within the building may have to be dismantled and removed before demolition.

(2) Advantages and disadvantages. Advantages and disadvantages of demolition are summarized in Table 8-4.

(3) costs. Cost for construction of replacement structures may be incurred. Operating costs for equipment are moderate to high. Costs for treatment and disposal of debris could be very high.

c. Dismantling.

(1) Description. Dismantling refers to the physical removal of selected structures or equipment from buildings or other areas. Unless decontaminated, dismantled

Table 8-4
Advantages and Disadvantages of Demolition

Advantages	Disadvantages
Technology is well-developed	Explosives and heavy machinery constitute hazards
Equipment is readily available	Personnel time could be extensive
Complete removal of contaminated materials from the site is expected	Accidental explosions may occur if combustible, explosive, or reactive residues are present
	Buildings, structures, and equipment are completely destroyed
	Large quantities of debris must be disposed
	Airborne contamination may occur through fugitive dust emissions
	Workers or nearby residents may be exposed

parts cannot be reused. Dismantling requires the use of major tools such as saws and blades for segmenting and removing. Nonsparking tools may need to be used if a combustible or ignitable material is present. Very thick metal parts (up to 0.4 in. or 1 cm) can be dismantled using plasma arc cutting; highly active parts can be dismantled using water shield plasma cutting; and very hard and thick materials such as steel and concrete can be dismantled with water jet cutting. Once dismantling is complete, all removed materials are decontaminated or placed in suitable containers and marked for shipment to a suitable disposal site.

(2) Advantages and disadvantages. Advantages and disadvantages of dismantling are summarized in Table 8-5.

(3) costs. Treatment costs are moderate to high considering the magnitude of the operation. Equipment and personnel comprise the bulk of this cost. As in demolition, the cost of the disposal of the debris could be very expensive.

d. Encapsulation.

(1) Description. Contaminated structures and equipment can be physically separated from the environment by a barrier. These barriers may be plaster, epoxy

Table 8-5
Advantages and Disadvantages of Dismantling

Advantages	Disadvantages
Removes only contaminated materials	Large quantities of debris must be disposed of as LLRW if the water from water jet cutting is sufficiently contaminated and needs to be treated prior to disposal
Potentially applicable to all types of contaminants	Remote removal may be necessary
Equipment is available from commercial manufacturers	Toxic fumes are possible from welding, cutting, and burning
	Dismantled parts cannot be reused unless decontaminated

resins, or concrete. Any loose contaminants such as liquids or sludges should first be removed. Loose solid materials can be removed with shearing equipment. Encapsulant are, at best, a temporary control measure. Control effectiveness depends primarily on the correct choice of encapsulant. Encapsulant are evaluated according to adhesive/cohesive strength, ability to adhere to substract, impact resistance, and toxicity.

(2) Advantages and disadvantages. Advantages and disadvantages of encapsulation are summarized in Table 8-6.

Table 8-6
Advantages and Disadvantages of Encapsulation

Advantages	Disadvantages
Large volumes of debris are not created	Contaminated material may not be removed from the site
No structural materials must be removed, which decreases worker exposure	Structures and equipment that have been encapsulated are inoperable and may have to be replaced
Equipment is common construction equipment	

(3) costs. Encapsulation usually involves moderate costs compared to the other decontamination techniques. Personnel costs will be smaller than with demolition and dismantling. Disposal costs will depend on whether the material is kept onsite or is shipped to a disposal site.

e. Gritblasting.

(1) Description. Gritblasting is a surface removal technique in which an abrasive material is used for uniform removal of contaminated surface layers from structures or equipment. Gritblasting can only remove surface contamination. Steel pellets, sand, alumina, or glass beads may be used as the abrasive. This method is ineffective for depths greater than about 0.5 to 1.5 cm, and the comers may not be gritblasted as effectively as flat surfaces. The removed surface material and abrasive are collected and placed in appropriate containers for treatment and/or disposal. Gritblasting should not be used on highly toxic residues and sensitive explosives. Secondary treatment may be necessary to remove contaminants that have penetrated the building material beyond the surface layer. This method requires a gritblaster, air compressor, debris collection system, and dust-suppression system. The equipment components of a gritlasting system are shown in Figure 8-7. A variant on grit blasting is the use of dry ice pellets or rubber/plastic pellets. Dry ice does need treatment, and rubber/plastic pellets are easily separated for reuse.

(2) Advantages and disadvantages. Advantages and disadvantages of gritblasting are summarized in Table 8-7.

Table 8-7
Advantages and Disadvantages of Gritblasting

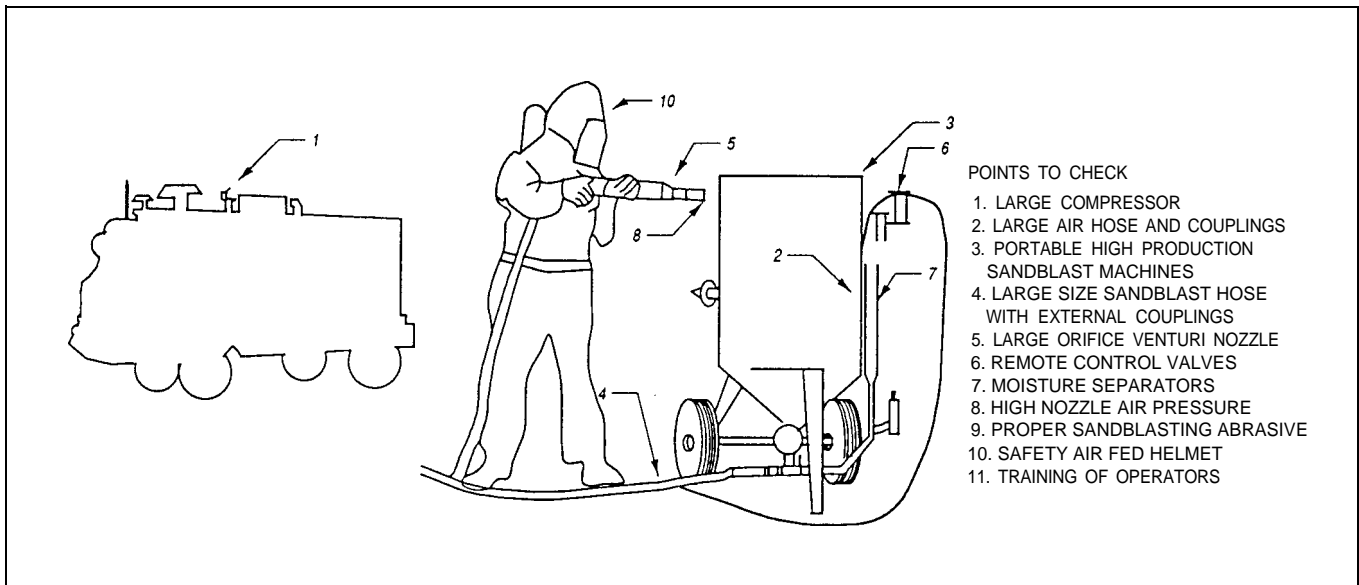| Advantages	Disadvantages
Widely used surface removal technique	Large amounts of dust and debris are generated
Large number of equipment manufacturers are available	A large quantity of abrasive is required
Remote control units available	Method is relatively slow
In most cases, minimal structural damages will result	Building or equipment is cleaned of residual dust by vacuuming and/or waterwashing; Dust inhalation creates a personnel hazard unless remote control units are used; Washing could produce a liquid waste that would require treatment prior to disposal

POINTS TO CHECK
1. LARGE COMPRESSOR
2. LARGE AIR HOSE AND COUPLINGS
3. PORTABLE HIGH PRODUCTION
   SANDBLAST MACHINES
4. LARGE SIZE SANDBLAST HOSE
   WITH EXTERNAL COUPLINGS
5. LARGE ORIFICE VENTURI NOZZLE
6. REMOTE CONTROL VALVES
7. MOISTURE SEPARATORS
8. HIGH NOZZLE AIR PRESSURE
9. PROPER SANDBLASTING ABRASIVE
10. SAFETY AIR FED HELMET
11. TRAINING OF OPERATORS

Figure 8-7. Equipment components of a gritblasting system (Source: Esposito et al. 1987)

(3) costs. Equipment and material costs are moderate compared to the other decontamination techniques. This method is labor-intensive unless remote control equipment is used. Remote control equipment is much more expensive than manually operated equipment. The disposal cost for the waste material also should be included in the economic analysis.

f. Hydroblasting/waterwashing.

(1) Description. Hydroblasting uses a high-pressure (3,500- to 350,000-kPa) water jet to remove contaminated debris from surfaces. The debris and water are collected, and the water is decontaminated. Hydroblasting may not effectively remove contaminants that have penetrated the surface layer. On the average, this technique removes 0.5 to 1.0 cm of concrete surface at the rate of 35 m^2/hr. The method can be used on contaminated concrete, brick, metal, and other materials. Hydroblasting can very easily incorporate variations such as hot or cold water, abrasives, solvents, surfactants, and varied pressures. A schematic diagram of a hydroblasting process is shown in Figure 8-8.

(2) Advantages and disadvantages. Advantages and disadvantages of hydroblasting are summarized in Table 8-8.

(3) costs. Repair costs of the treated surfaces should be low to moderate. Fuel and equipment costs should be moderate, and personnel costs will be high

Table 8-8
Advantages and Disadvantages of Hydroblasting

Advantages	Disadvantages
Uses off-the-shelf equipment	Not applicable to wood or fiberboard
Surfactants, caustics, or commercial cleaners can be added to decrease surface tension and effectiveness	Large amounts of contaminated liquid will be generated, which will require treatment
Remotely operated rigs can be used on walls and floors	May not effectively remove subsurface contaminants
Solvents such as acetone can be used with water or in place of water to solubilize contaminants	
Sand or other abrasives can be used to increase surface removal effectiveness	

unless a remote system is used. In that case, personnel costs will be low but equipment costs will be high.

g. Painting/coating.

(1) Description. Three separate processes fall under this general heading: (a) paint removal, (b) fixative/ stabilizer coatings, and (c) strippable coatings. Paint removal might be needed in a building found to contain radiation contamination where the radioactive material is
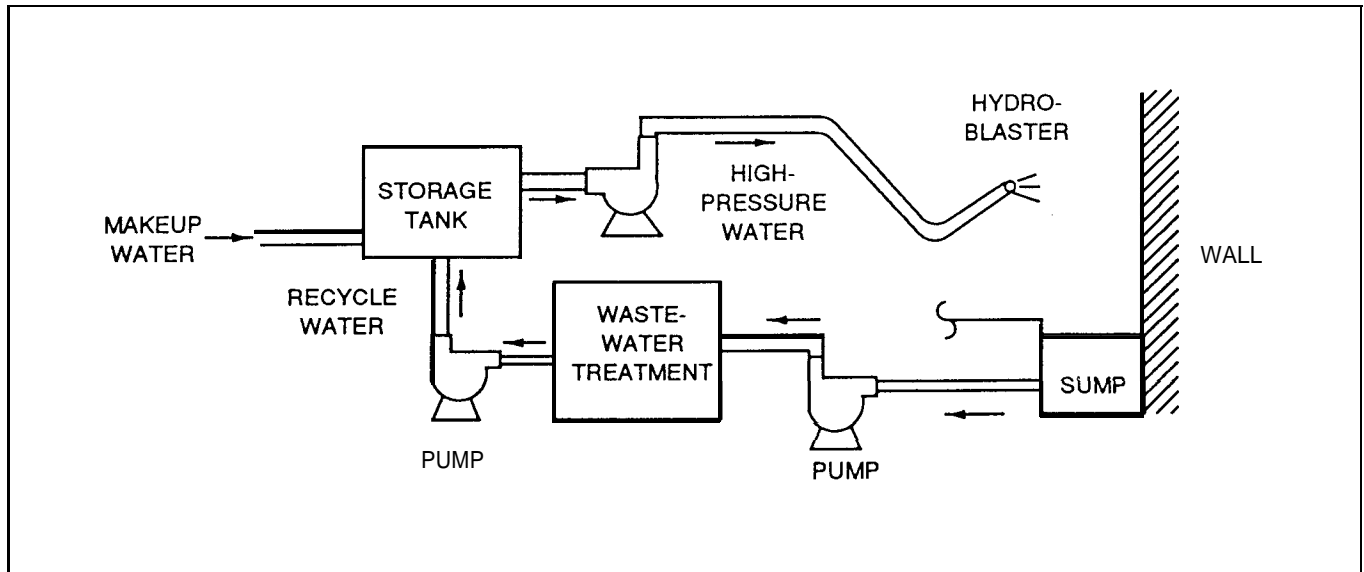
Figure 8-8. Schematic diagram of the hydroblasting process (Source: Esposito et al. 1987)

on the wall surface or trapped between layers of paint. A combination of commercial paint removers, handscraping, waterwashing, and detergent scrubbing is used to remove the paint. Fixative/stabilizer coatings can be used on contaminated residues to fix or stabilize the contaminant in place and decrease or eliminate exposure hazards. These agents include molten and solid waxes, carbo-waxes, organic dyes, epoxy paint films, gels, foams, and polyester resins. To create strippable coatings, compounds that bind with contaminants are mixed with a polymer, applied to a contaminated surface, and removed to achieve decontamination.

(2) Advantages and disadvantages. Advantages and disadvantages of painting/coating are summarized in Table 8-9.

(3) costs. For paint removal, treatment, labor, and disposal costs should be moderate. Major costs will be incurred for resurfacing, if needed. When fixative coatings are used, treatment and labor costs will be somewhat lower than the other techniques, and disposal costs will be minimal. Strippable coatings must be applied and removed so the treatment and labor costs are greater. Equipment is available at low cost.

h. Scarification.

(1) Description. Scarification is capable of removing up to 2.5 cm of surface layer from concrete or similar materials. It is applicable only to concrete (not concrete

Table 8-9
Advantages and Disadvantages of Painting/Coating

Advantages	Disadvantages
Requires little equipment	Labor-intensive operation
Well-developed technique	Worker exposure potential is high
Very little hazardous waste is generated by fixatives	Paint removal usually takes longer than painting
Coatings are applicable to all building materials	Fixative coatings must be monitored over their lifetime
Fixative coatings reduce the level of contamination to which building occupants are exposed	Hard to achieve the intimate contact between fixative and contaminant needed on a rough surface
Stripped coating physically holds or traps the contaminant for easier handling and disposal	Strippable coatings may bind to the surface as well as the contaminant, which may result in large volumes of waste and structural damage
Different polymer formulations may be required for various building materials	Paint removal may be needed prior to application of strippable coating

block) and cement. The scarifier tool consists of pneumatically operated piston heads that strike the surface, causing concrete to chip off. The piston heads consist of mulTipoint tungsten carbide bits. An almost identical process to scarifying is scabbling, in which a suer-high-pressure water system can be used. This water system is

more easily operated remotely. Wall, floor, and hand-held scarifies are available. The tungsten-carbide bits have an average working life of 80 hr under normal conditions. Actual experiences have shown that a seven-piston floor scarifier can remove approximately 30 m^2 of surface material per hour and a three-piston wall scarifier can remove 7 to 10 m^2 per hour. The units may be modified to include a HEPA-filtered vacuum exhaust system to capture contaminated dust. Remotely operated scarifier rigs can be used.

(2) Advantages and disadvantages. Advantages and disadvantages of scarification are summarized in Table 8-10.

Table 8-10
Advantages and Disadvantages of Scarification

Advantages	Disadvantages
Potentially applicable to all contaminants except highly toxic residues or highly sensitive explosives	Substantial amounts of contaminated debris (water, concrete, and dust) are generated
Achieves a deeper penetration than most other surface removal techniques	The treated surface retains a rough appearance that requires resurfacing
	An explosion potential exists if pockets of combustible material are encountered
	Not suitable for hard-to-reach areas or for metal, wood, etc.
	Personnel hazards may result from high noise levels, contaminant-laden dust, and flying chips

(3) costs. Repair costs for the surface should be moderate. Equipment costs are moderate to high, but fuel costs should be low. Manpower costs will probably be high because the removal rate is quite slow. Disposal costs will be moderate to high.

i. Solvent washing.

(1) Description. In solvent washing, an organic solvent is circulated across the surface of a building to make contaminants soluble. A diagram of the solvent is presented in Figure 8-9. If no degradation of the solvent occurs, the spent solvent can be either thermally or chemically treated to remove the contaminants. This method has potential applications to a wide range of contaminants and building materials. The primary difficulty is to achieve an inward flux of solvent into porous building materials followed by an outward flux of solvent contaminated with residues.

(2) Advantages and disadvantages. Advantages and disadvantages of solvent washing are summarized in Table 8-11.

(3) costs. Equipment and material costs will be moderate to high. Manpower costs could possibly be extensive. Disposal costs will be moderate to high.

j. Steam cleaning.

(1) Description. Steam cleaning physically extracts contaminants from building materials and equipment surfaces. Currently, steam cleaning is used mainly to remove contaminated particulate. This technique is known to be effective only for surface decontamination. Steam cleaning requires steam generators, spray systems, collection sumps, and waste treatment systems. Commercial-scale steam cleaners are available from many manufacturers. Several manufacturers make portable steam cleaning equipment.

(2) Advantages and disadvantages. Advantages and disadvantages of steam cleaning are summarized in Table 8-12.

(3) Costs. Steam cleaners are generally moderately priced. Manpower and waste disposal costs will be high.

k. Drilling and spalling.

(1) Description. Drilling and spalling consists of drilling holes which are 2.5 to 4 cm in diameter and 7.5 cm deep into concrete. The spalling tool bit is inserted into the hole and hydraulically spreads to span off the contaminated concrete. This technique can remove up to 5 cm of surface from concrete or similar materials. Vacuum filter systems and water sprayers can be used to control dust during drilling and spalling operations. Remotely operated drill and span rigs are available. A sketch of a concrete spaller is given in Figure 8-10. Battelle Pacific Northwest reports that its drilling and spalling rig has an average removal rate of 6 m^3/hr for standard concrete.

(2) Advantages and disadvantages. Advantages and disadvantages of drilling and spalling are summarized in Table 8-13.

WALL

INERT SEAL

SOLVENT
CIRCULATION
UNIT

FILTER

PUMP

SOLVENT
FEED TANK
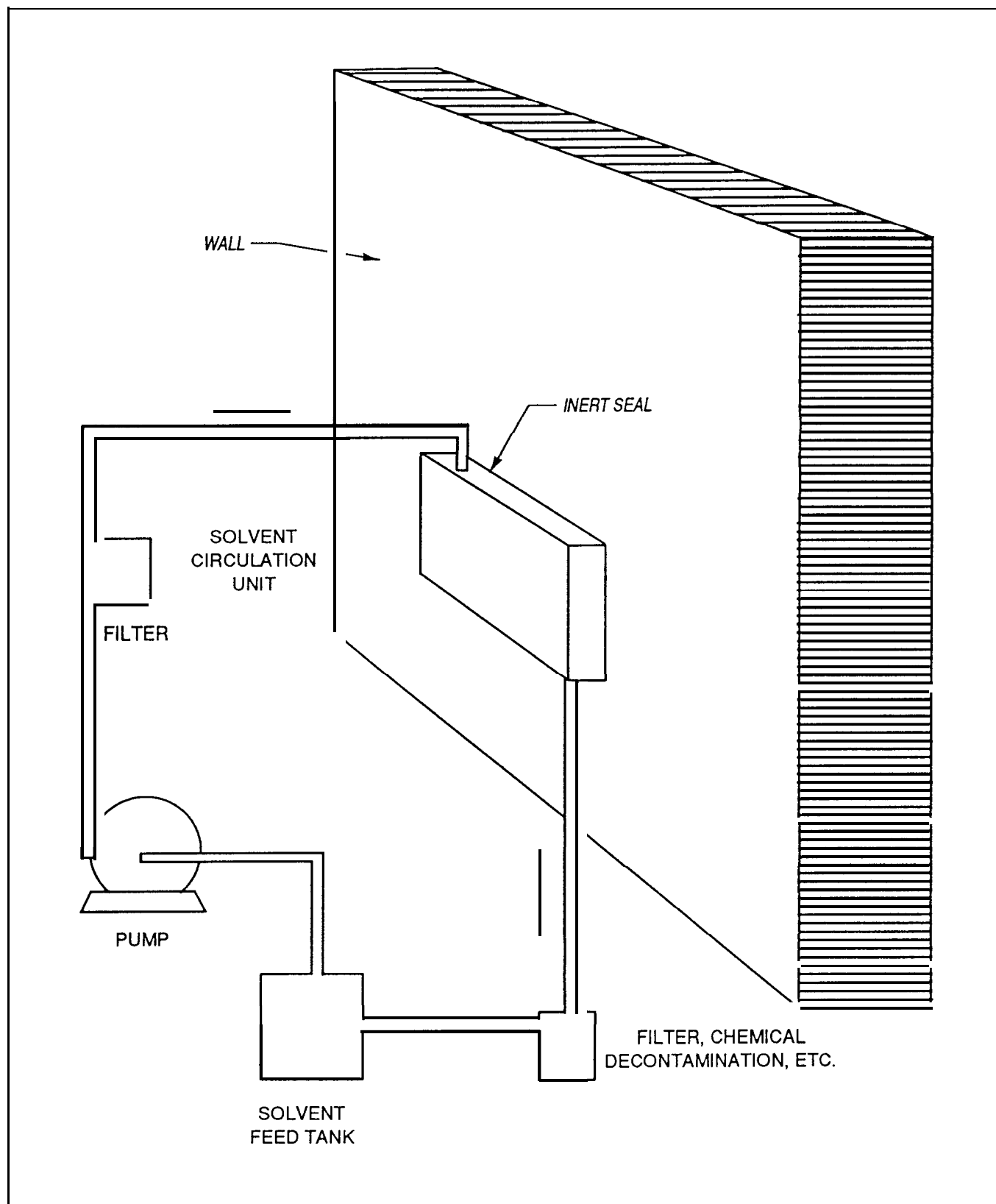
FILTER, CHEMICAL
DECONTAMINATION, ETC.

Figure 8-9. Schematic diagram of the solvent circulation apparatus (Source: Esposito et al. 1987)

Table 8-11
Advantages and Disadvantages of Solvent Washing

Advantages	Disadvantages
Depending on the solvent-contaminant match, this can be a very efficient removal system	Penetration of the solvent into the material matrix, followed by outward diffusion, may require a long time
Removal of contaminated paint is possible if the proper solvent is used	It may be extremely difficult to get a tight seal around the solvent circulation apparatus and surface
	Not suitable for intricate structures
	Probably will require extensive set-up time
	Residual solvent may require removal; solvent may be hazardous waste

Table 8-12
Advantages and Disadvantages of Steam Cleaning

Advantages	Disadvantages
Relatively inexpensive and simple technique	Labor-intensive process that is costly if automated
Depending on the contaminant, thermal decomposition and/or hydrolysis may occur	Large volumes of contaminated water are generated (although these are generally less than in hydroblasting)
	Personnel hazards include the potential for steam burns and toxicity from solvent/steam mixtures

(3) Costs. Costs for resurfacing are expected to be moderate. Equipment, manpower, and disposal costs will be high in comparison to the other decontamination methods.
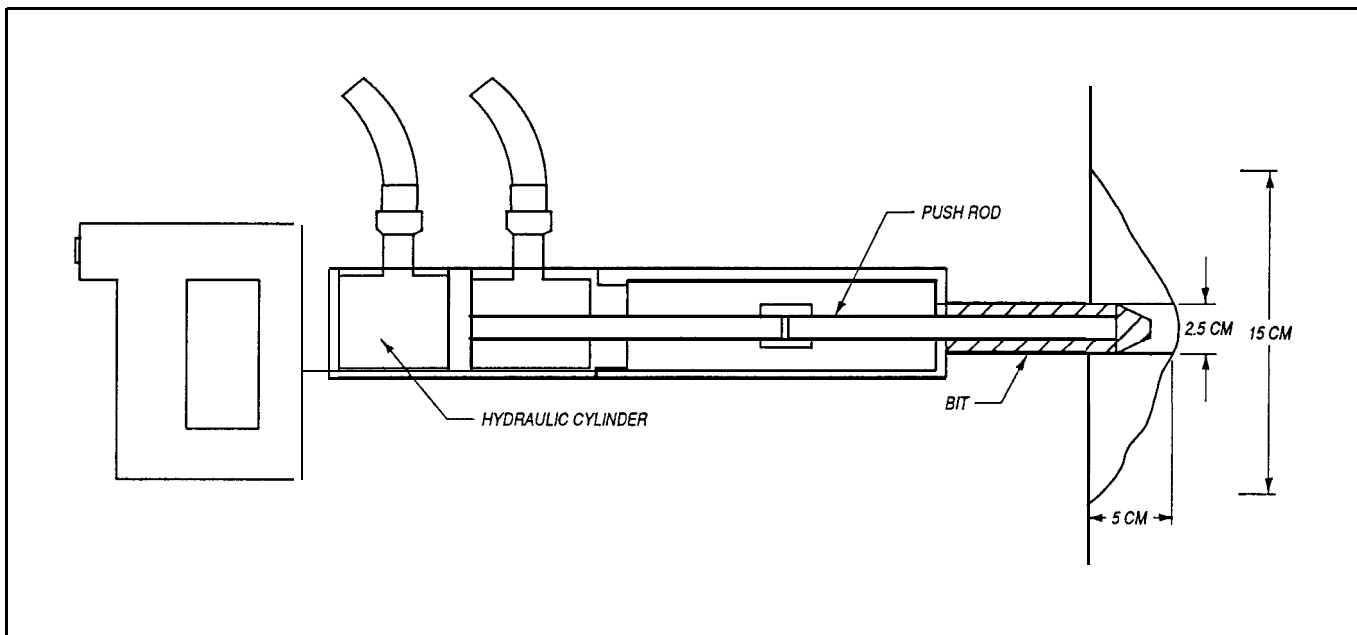

Figure 8-10. Concrete spaller (Source: Esposito et al. 1987)

1. Foam and gel decontamination.

(1) Description. Foam and gel applicators produce solutions that adhere to the surfaces being decontaminated and provide a means to clean surfaces where soaking action is required. The foam is produced by a pressurized applicator, it adheres to the surface, and the surface is decontaminated through contact and chemical removal. The gel works on the same principles as the foam, except the gel can adhere to the surface for a longer period of time. This will increase the decontaminability due to a longer soaking time. Nitric acid has been used at the Savannah River site as the decontamination agent.

Table 8-13
Advantages and Disadvantages of Drilling/Spalling

Advantages	Disadvantages
Achieves deeper penetration of surfaces than other surface removal techniques	Substantial amounts of contaminated debris are generated
Works well for large-scale applications	High dust and noise levels pose personnel hazards
	No combustible residues can be present
	Applicable to concrete only (not to concrete blocks) and will have to be modified or another technique chosen to treat other building materials
	Personnel time is extensive because this is a relatively slow process and large quantities of concrete will have to be collected.
	Spalled surface is very rough and may require concrete capping or some other treatment to yield smooth surfaces

Table 8-14
Advantages and Disadvantages of Foam Decontamination

Advantages	Disadvantages
Decontaminated surface is not damaged in this process	Useful only for smearable contamination
The operator can easily see the surfaces being treated, and the foam can be applied remotely	The foaming agent and decontamination agent must be compatible and mixed in the correct order and amounts
Foam and gel are easy to apply	
Only a small amount of waste products are generated	
Portable equipment can be obtained if needed	

Table 8-15
Advantages and Disadvantages of the Kelly Machine

Advantages	Disadvantages
Commercially available and has been proven effective	Large volume of contaminated water will be generated
Can be modified to be used remotely	The use of superheated water poses a personnel hazard
	Only useful for smearable contamination

(2) Advantages and disadvantages. Advantages and disadvantages of foam decontamination are summarized in Table 8-14.

(3) Costs. Cost information was not available.

m. Kelly machine.

(1) Description. This system sprays superheated water on a surface and vacuums the spent liquid into a reservoir. The use of superheated water is expected to increase the decontamination factor achieved. A Kelly decon machine is used in a teleoperated system at the Savannah River site.

(2) Advantages and disadvantages. Advantages and disadvantages of the Kelly machine are summarized in Table 8-15.

(3) Costs. Cost estimates were unavailable.

8-4. Solid-Liquid Separation

a. Suspended solids.

(1) Evaporation.

(a) Evaporation is considered a volume reduction method as well as a separation method. Considering that evaporator technologies are controlled by physical and chemical characteristics of the waste streams and not by their radioactivity, almost any type of evaporation technology can be applied to LLRW consistent with keeping radiation exposures as low as reasonably achievable. Evaporation concentrates liquid effluent by using heat to drive off waste components in the order of their volatilization temperatures. Water usually has one of the lower volatilization temperatures. The basis for evaporation is simply the separation of volatile from nonvolatile material.

(b) A generalized flow diagram is presented in Figure 8-11. The system works as follows (the numbers in parentheses correspond to flows in the figure): the feed consists of water contaminated with low concentrations of
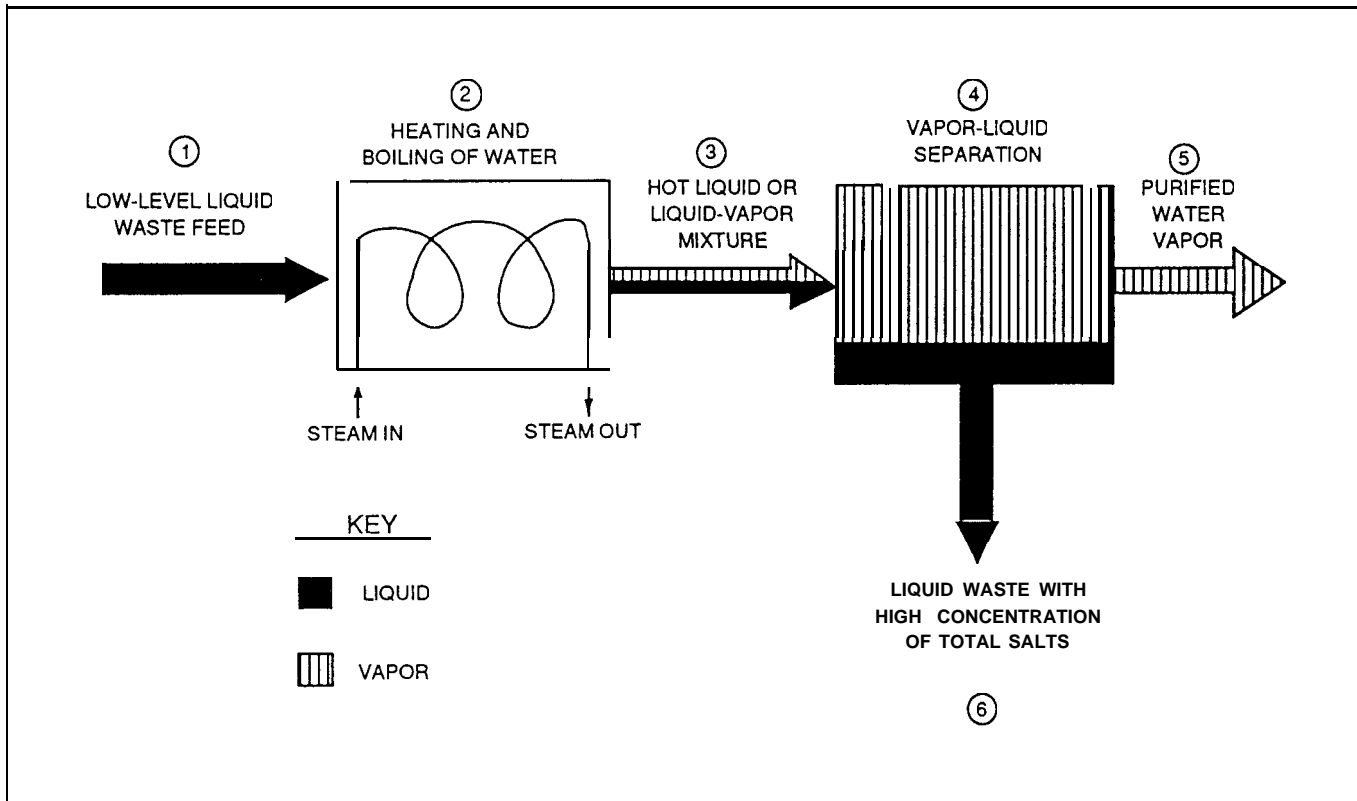
Figure 8-11. Simplified evaporation process (Copyright © 1991. Electric Power Research Institute. EPRI NP-7386-V1. *Radwaste Desk Reference, Volume 1: Dry Active Waste.* Reprinted with permission.)

radioactive material; the feed is heated with steam in a heat exchanger, boiling off some of the water; this produces a mixture of hot liquid and evaporated water vapor; the vapor and liquid are separated into two streams: relatively pure water vapor, and a liquid solution highly concentrated with nonvolatile radioactive material. The highly concentrated liquid is only a fraction of the volume of the feed solution, greatly reducing the quantity of material requiring special radioactive waste disposal techniques. Energy from the purified water vapor may be reused to provide steam for the heating and boiling step. Heat transfer is the most important aspect of evaporator design. In general, the heater is designed so that LLRW feed is delivered to the inside of the tubes with steam contacting the outside of the tube surface.

(c) Natural circulation evaporators have long vertical heat exchanger tubes so that the contaminated liquid flows upward through the tubes (rising film) or the liquid flows downward (falling film) through the tubes. Although operating costs are relatively low with natural circulation evaporators, they have been replaced by more effective forced-circulation evaporators.

(d) In a rising-film evaporator, the waste feed is delivered to the bottom of the heater. Liquid on the inside of the heater tubes is brought to a boil by steam. Natural circulation occurs because the rising vapor helps move the liquid upward. As the fluid moves up the tube, more vapor is formed, causing a thin film of liquid to form along the tube surface. This improves the heat transfer and allows more water to boil off.

(e) With falling film evaporators, the waste feed is delivered to the top of the heater and the liquid flows downward due to gravity. The heat transfer performance of this configuration is improved because a thinner, faster moving film is produced. Falling film heaters are smaller than rising film heaters. The falling film evaporator has a pump to circulate the liquid to the top of the unit. It is not used for forced circulation. The chief problem with the falling film evaporator is the difficulty of attaining uniform liquid distribution at the top of the tubes.

(f) The most common type of forced-circulation evaporator is the evaporator crystallizer. The process is

similar to the rising-film evaporator, except that a larger recirculation pump is used to enhance circulation, and the heater does not boil the liquid. In this process, liquid waste feed is mixed with a relatively large portion of concentrated liquid waste and fed at a high rate through the heater. The liquid is heated less than 10 "F by the heater. As the liquid enters the vapor body, where the pressure is slightly less than in the heater tubes, some of the liquid evaporates. The vapor enters an entrainment separator and then a condenser. The majority of the concentrated liquid waste coming out of the vapor body is recirculated. This allows the circulating liquid to be a suspension of dissolved salts and undissolved salt crystals. The equipment is designed to handle circulating solids. This process is illustrated in Figure 8-12. The major advantage to this type of system is that greater waste volume reduction can be achieved. However, operating costs are high, because of extensive pumping requirements.

(g) Wiped-film evaporators (sometimes called agitated-film, thin-film, or scraped-film evaporators) use a hot fluid inside a tube to heat the LLRW and evaporate water. Liquid waste is spread on the outside of the tube by a rotating assembly of blades, creating an easily evaporated thin film.

(h) It is often economical to use the steam produced in the evaporator to provide the energy to evaporate water from the liquid waste feed. This process is termed vapor recompression. The low-grade steam coming out of the entrained liquid separator is delivered to a compressor. The compressor increases the pressure and temperature of this steam. This steam is supplemented by a small amount of makeup steam and then sent to the heater. Vapor recompression can result in energy savings of over 80 percent.
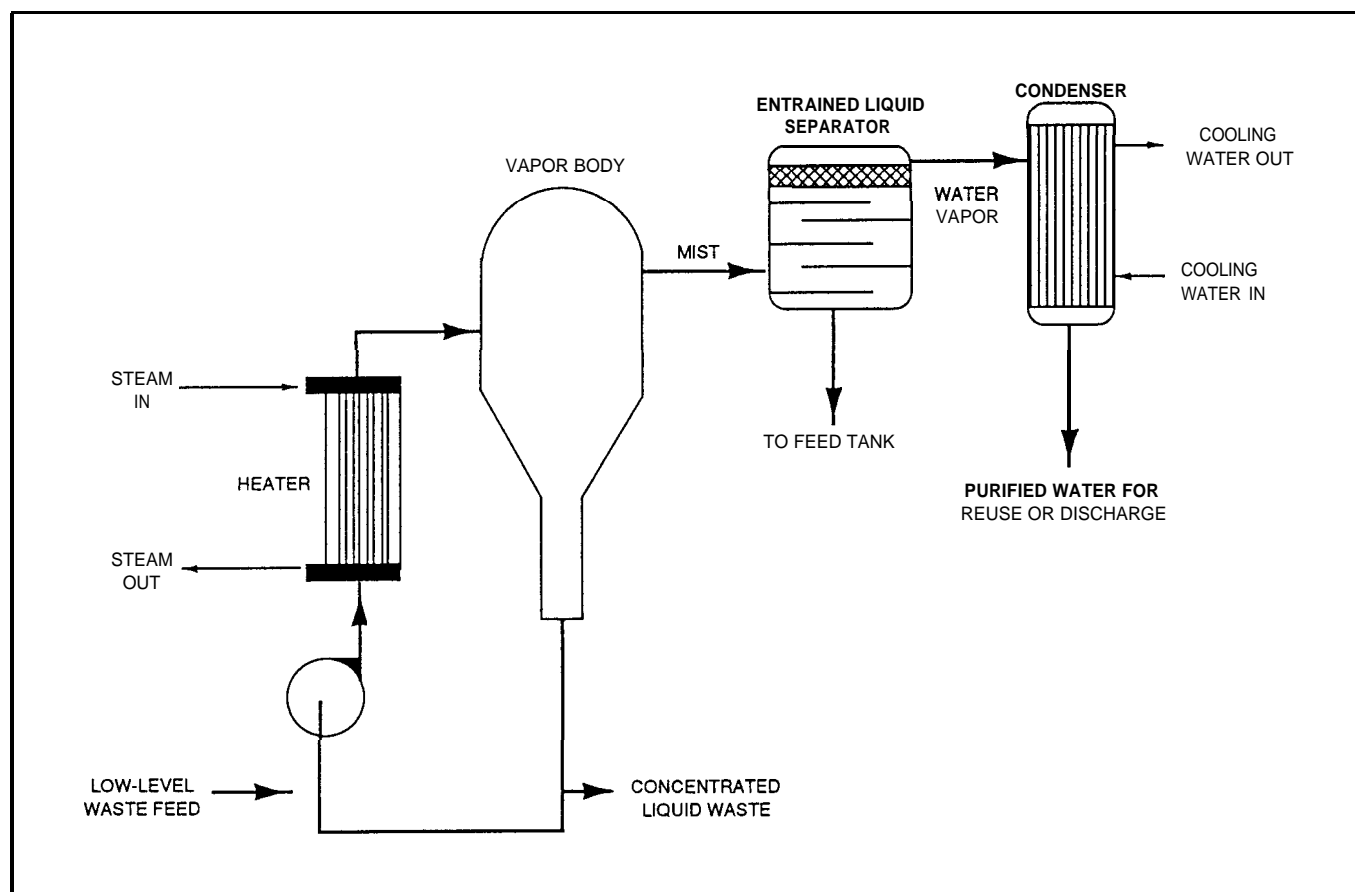

Figure 8-12. Forced-circulation evaporator (Copyright © 1991. *EPRI NP-7386-V1. Radwaste Desk Reference, Volume 1: Dry Active Waste.* Reprintad with permission.]

(i) Multiple-effect evaporators provide another means of increasing energy utilization. This evaporator system uses the vapor from one evaporator as the heating source for the next (more concentrated liquid) evaporator in the system. In this way, the steam is used a number of times, reducing the system energy costs. Vapor recompression between evaporators is not required since successive evaporators are normally operated at lower absolute pressures. This evaporator type is normally used only for large-scale applications.

(j) Table 8-16 outlines the advantages and disadvantages of each evaporator type. A main advantage of evaporation is that the process usually produces residues with a water content of 1 to 5 percent. The main constraints encountered in evaporation processes relate to corrosion phenomena, to scaling and formation of incrustation, to the presence of interfering compounds such as certain unstable nitrates, organics, foaming agents, and, not the least, to the problem of generation and removal of dust. Anti-foam agents added to foaming evaporators

Table 8-16
Advantages and Disadvantages of Evaporator Types Used in Light-Water Reactor Power Plants

	Evaporator Type		
	Natural Circulation	**Forced Circulation**	**Forced Circulation with Vapor Recompression**
Advantages	• Low-cost • Large heating surface • Low holdup time • Small floor space • Good heat-transfer coefficients at reasonable temperature differences (rising film) • Good heat-transfer coefficients at all temperature differences (falling film)	ž High heat-transfer coefficients • Positive circulation • Relative freedom from salting, scaling, and fouling	In addition to those for forced circulation: • Cooling water requirements are eliminated • Steam heating requirements are reduced
Disadvantages	• High head room • Generally unsuitable for salting and severely scaling liquids • Poor heating transfer coefficients of rising-film version at low temperature differences • Recirculation usually required for falling-film version	• High cost • Power required for circulating pump • Relatively high holdup or residence' time	• High cost • Electrical consumption high due to large compressor motor • Relative high holdup or residence time
Best Applications	• Clear liquids • Foaming liquids • Corrosive solutions • Large evaporation loads • High temperature differences-falling film • Low temperature operation-falling film	• Crystalline product • Corrosive solutions • Viscous solutions	• Crystalline product • Corrosive solutions
Frequent Difficulties	• Sensitivity of rising-film units to changes in operating conditions • Poor feed distribution of falling-film units	• Plugging of tube inlets by salt deposits detached from walls of equipment • Corrosion-erosion problems resulting from improper feed pH adjustment	• Same as normal forced-circulation evaporators

frequently overcome the problems caused by foaming agents such as detergents.

(k) Just as evaporators can be used to reduce large volumes of liquid LLRW, they can also be used to reduce volumes of dilute liquid mixed waste. Evaporation may also be useful as a separation technique, provided the hazardous components are evaporated, collected, and then treated. An evaporator may be considered by the EPA or a delegated state program as a treatment facility requiring an RCRA Part B permit if the liquid undergoing treatment is considered to be "solid waste. "

(1) A properly designed shielding and containment system around the evaporation equipment provides for control of radioactive emissions and protection of employees at the facility. ALARA requirements are important, since evaporation actually concentrates the radioactivity.

(2) Centrifugation.

(a) Centrifuges are used to achieve partial dewatering of solid-liquid suspensions like sludges, obtained by filtration or chemical flocculation of liquid effluents, as well as spent ion-exchange resins. The principle of operation is a liquid-solid separation by centrifugal forces.

(b) Centrifuges are used both for continuous and batchwise operations in nuclear power stations and in nuclear research centers that use chemical flocculation processes. In the latter case, freeze-thawing or gravity thickening is used to overcome the problems related to the colloidal structure of the sludges. The system's applicability is limited to large particles unless additional filtering layers or polyelectrolytes are used.

(c) Typical process data indicated throughputs of 1 to 5 m^3 feed slurry per hour, with feed solids content from 0.01 to 1 percent by weight (t %). The dewatering performance largely depends on the solids characteristics, and the residual water in the solids varies between 5 (granular) and 90 wt % (colloidal sludges). Horizontal and vertical centrifuges are being used at 4,000 to 6,000 rpm.

(3) Filtration.

(a) Filtration is applicable to chemical sludges, obtained from flocculation and co-precipitation of liquid effluents, as well as to suspensions originating from backwash cleaning of larger filter units. The process aims at volume reduction, by dewatering before any further treatment or immobilization, and is based on the separation of solids on a porous material through which the liquid phase passes. Two main filtration techniques are applied - vacuum filtration and pressure filtration.

(b) Vacuum filtration is the most common type of filtration. Continuous units are commercially available and are based on horizontally rotating cylinders with filter cloth or porous metal, on which the filter cake is accumulated during the slow rotation. The filter cake is scraped off at the end of each rotation. The capacity is limited by the filtration characteristics of the sludge, and the equipment size is large compared with pressure filtration units. Because of its design and principle of operation, vacuum filtration is compatible with radiological safety requirements and allows for treating low-level as well as intermediate-level sludges, with low exposure to personnel and low potential for the spread of contamination. Dewatering up to 20- to 40-wt % solids can be obtained for wastes with initial 1- to 10-wt % solids content.

(c) Pressure filtration offers the advantage of increased filtration rate and compact equipment, but it has the disadvantage of the risk of leakages, because it operates under pressure. Pressure filtration units can consist of filter cartridges or horizontal and vertical multilayer plate configurations. Semi-continuous operation is obtained in the vertical one by centrifugal cleaning of the discs. In general, pressure filtration has the disadvantage that, in the case of poor filterability of the sludges, precoat filter aids, such as cement or diatomaceous earth, have to be used, which results in an increase in the final waste volume.

(d) A good example of a filtration system for heavy metals and radionuclides is the filter method developed by Filter Flow Technology, Inc. This colloidal filter method removes inorganic heavy metals and non-tritium radionuclides from industrial wastewater and groundwater. The filter unit has an inorganic, insoluble filter bed material contained in a dynamic, flow-through configuration resembling a filter plate. A three-step process is used to achieve heavy metal and radionuclide removal. First, water is treated chemically to optimize formation of colloids and colloidal aggregates. Second, a prefilter removes the larger particles and solids. Third, a filter bed removes the contaminants to the compliance standard desired. The process is designed for either batch or continuous flow applications at fixed installations or field mobile operations. The field unit can be retrofitted to existing primary solids water treatment systems or used

as a polishing filter for new installations or onsite remediation applications.

(4) Freeze-thawing.

(a) A possible pretreatment step for colloidal sludges prior to centrifuging or filtration is the freeze-thawing process. The colloidal suspensions are first completely frozen (-15 "C to -20 "C) and, after thawing, show improved settling characteristics. The physical process occurring is tri-dimensional cracking of the colloidal network into a more granular structure. Drawbacks of this process are the energy balance, corrosion problems, and the discontinuous small scale of operation.

(b) The process is applied to sludges with relatively low specific activity (0.1-5 μCi/g dry solid). Direct dewatering of 12 wt % of solids content has been obtained, starting with sludges concentrated by gravity to 6 wt % solids.

(5) Membrane processes.

(a) Various types of membranes exist that are able to filter different size molecules. Reverse osmosis (RO) and ultrafiltration can be used as LLRW treatment processes. In membrane processes, contaminants are separated from a solvent (water) by the movement of the solvent through a semipermeable membrane. The contaminants are filtered out by the membrane.

(b) Reverse osmosis removes contaminants from aqueous wastes by passing the waste stream, at high pressure, through a semipermeable membrane. At sufficiently high pressure, usually in the range of 1,378 to 2,756 Pa (200 to 400 psi), pure water passes out through the membrane, leaving a more concentrated waste stream. The semipermeable membrane itself is the most critical part of the RO process. Membranes are manufactured from a variety of materials such as cellulose acetate, cellulose diacetate, cellulose triacetate, polyamide, other aromatic polyamides, polyetheramides, polyetheramines, and polyuetherurea. Cellulose acetate and cellulose triacetate membranes can be prepared in sheet form with water fluxes of 4.1 $x\,10^{-2}$ to 8.2 $x\,10^{-2}\,m^{3}/day/m^{2}$ at 2,756 kPa (400 psi). Polyamide and thin-film composite membranes are subject to degradation if exposed to chlorine or other oxidants. RO membranes can be spiral wound, hollow fine fiber, tubular, or flat. The configuration depends upon the volume of water needing treatment. One of the major difficulties with RO membranes is their susceptibility to fouling. It is common practice to pretreat the water to remove oxidizing materials, iron,

and magnesium salts, particulate, and oils, greases, and other film formers. The pH and temperature of the feed water may also need to be adjusted. RO membranes can filter particles in the O .001 -micron to 0 .05-micron size range.

(c) Ultrafiltration (UF) is similar to reverse osmosis in that both processes involve the transport of a solution under a pressure gradient through a semipermeable membrane to achieve separation of solvent molecules from solute molecules. Ultrafiltration is not impeded by osmotic pressure and can be performed at low pressure differences of 34.5 to 689 kPa (5 to 100 psi). Ultrafiltration is applicable to solutes with molecular weights between 500 and 500,000. Above this molecular weight size, separation occurs by conventional filtration. UF membranes are commercially available in cellulose acetate, polysulfone, acrylic, polycarbonate, polyvinyl chloride, polyamides, polyvinylidene fluoride, copolymers of acrylonitrile and vinyl chloride, polyacetal, poly - acrylates, polyelectrolyte complexes, and cross-linked polyvinyl alcohol. Membrane configurations are available in tubular, plate-and-frame, spiral-wound, and hollow-fine-fiber designs. Temperature has an increased effect in ultrafiltration operation. Fluxes through the membrane tend to double with a 15 °C to 25 °C rise in temperature. Operating temperatures are limited by economics and the membrane material. Membranes produced from cellulose are limited to the 50 °C to 60 °C range, while other membranes may be operated at temperatures as high as 100 °C. Ultrafiltration membranes do not require pretreatment as extensive as RO membranes. In fact, ultrafiltration can be used as a pretreatment for RO. Ultrafiltration affects particles in the 0.003-micron to 1-micron size range. France has developed a process for treating laundry liquid wastes with low-level contamination by cobalt, cesium, and silver by mineral ultrafiltration membranes.

(d) Membrane processes are very effective separation processes. They are well-suited to small flows and small installations. Recent membrane advances have reduced the capital, operation, and maintenance costs required, but these costs are still significant when compared to more conventional water treatment techniques. The maintenance problems related to membrane fouling and the pretreatment requirements are definite disadvantages that should be considered when comparing membrane processes to other treatment processes.

b. *Dissolved solids.* Treatment processes for dissolved solids such as precipitation, carbon adsorption, alumina adsorption, and ion exchange are discussed in

Chapter 12 for the treatment of mixed wastes. These techniques are well-developed, with extensive literature bases.

8-5. Immobilization

a. Cement.

(1) Introduction. Cement, which has a basic composition of calcium, silicon, aluminum, and iron oxides, is commonly used as a matrix material for the solidification and immobilization of radioactive and hazardous wastes. The major benefit from any of these processes is the binding together of the particles to avoid dispersion and to reduce the surface area exposed to air or water transport. Structural stability is convenient for placement and maintaining the integrity of the system.

(2) Composition. Hydraulic cement can be defined as the general class of cementations materials that require addition of water and solidify as a result of various hydration reactions. When cement and water are mixed together, a series of chemical reactions begin that result in stiffening, hardening, evolution of heat, and, finally, development of long-term strength. The most significant is the hydration of calcium silicates, which constitute about 75 percent of the weight of cement, to form calcium hydroxide and cement gel. Hydrated cement contains about 25 percent calcium hydroxide and 50 percent cement gel by weight. The strength and other properties of hydrated cement are due primarily to cement gel. It acts as the principal binder and hardener in the portland cement/water system. There are five types of portland cement with well-defined properties designated Types I to V. Type I cement is a general-purpose cement. Type II cement is a slow-setting, sulphate-resistant cement and produces only a moderate amount of heat during setting. Type III cement is fast-setting, with high compressive strength, but generates significant heat during setting. Type IV is a slow-setting cement with low heat generation. Type V cement is highly resistant to sulfate and is generally used in marine environments. The choice of cement is highly dependent upon the waste being processed. Most vendors consider their formulations to be proprietary.

(3) Pozzolan. Mixtures of hydraulic cement with fly ash, pumice, lime kiln dusts, or blast furnace slag are normally called "pozzolan" mixtures. By adding the pozzolan to the cement, the strength and durability of the immobilizing matrix can be improved. However, pozzolanic reactions are generally much slower than cement reactions.

(4) Grout and concrete. Cement mixed with sand and water is called "grout." Grout is used in situations where it must fill small voids. Cement mixed with water, sand, and gravel is called "concrete."

(5) Water-to-cement ratio. A minimum water-to-cement ratio is approximately 0.40 by weight for portland cement but depends on the waste itself, since some waste solids absorb large amounts of water. The addition of too much water may result in a layer of free-standing water on the surface of the solidified product as well as a reduction in strength and an increase in the permeability of the final waste form, which is a grout-waste solid matrix.

(6) Additives. Additives can be used to improve the waste/grout compatibility or to reduce the water/cement ratio.

(a) Common additives. Common additives include sodium-silicates, zeolites, clays, and formaldehyde. The sodium-silicates, zeolites, and clays provide improved settings for different waste materials, while the formaldehyde prevents bacterial growth which can cause internal build-up of gas pressure.

(b) SuperPlasticizers. The addition of superplasticizers (water-reducing admixtures) would allow for lower water/cement ratios. These admixtures are surfactants that act by adsorbing to the surface of the cement particles so that the surface of the cement particle becomes hydrophilic, and it is no longer attracted to other cement particles. A better-dispersed suspension of the cement paste means that a lower water/cement ratio can be used to lower permeability without a change in consistency, and a higher waste loading can be achieved. A 25- to 30-percent water reduction is possible with superplasticizers, decreasing the porosity and increasing the strength of the final product.

(c) Silica fume. Another admixture that tends to increase the durability and decrease the porosity of cement is silica fume, or microsilica. The microsilica particles are much smaller (diameter ratio is approximately 1/100) than the cement particles, allowing them to physically fill the void spaces between the cement particles. The microsilica also changes the hydration reaction in the cement so that more cement gel is formed. The additional gel improves bonding within the cement-waste matrix and helps reduce permeability. The addition of microsilica requires additional water or water-reducing admixtures to allow for adequate dispersion.

(d) Polymer mixtures. Portland cement is preferred for use in these mixtures because it is a common, inexpensive construction material. Typical construction concrete mixtures are often used to immobilize solid material. However, heavy materials such as barite and hematite are added in some instances to increase shielding effectiveness. Concrete impregnated with polymers can improve the properties of the grout-waste form considerably. The polymers decrease the rate of leaching and shrinkage and improve the strength, durability, and chemical resistance of the waste form. A disadvantage to using polymers is that the waste mixture might need to be heated, which increases the capital, operating, and maintenance costs of the system. (Polymers are discussed further in Section 8-5. *c.*)

(7) Inorganic cements. Delaware custom material (DCM) and Envirostone are patented inorganic cements. DCM is a sodium silicate solution incorporating a setting agent, usually portland cement. Envirostone is a polymer-modified, gypsum-based cement that has been ground to a fine powder. It has a different chemistry than portland cement and can incorporate waste such as berates that can cause failure of cementitious systems. In an aqueous waste, the use of Envirostone results in a uniform cast containing no free liquid. Envirostone works best on neutral to acidic wastes. Envirostone is relatively expensive ($0. 678/lb) as compared to portland cement ($0.06/lb).

(8) Cement glass. Cement glass can also be used for solidification. The water-to-cement glass ratio is approximately 0.3, with a very low viscosity. Thus, it must be contained in a high-integrity container (HIC). The sodium and phosphorus silicate for the cement glass is obtained from clay, so it is very low in cost. The cement glass has inorganic polymer characteristics with the fine structure and intense strength of glass. The matrix is inert to the waste, so no chemical reaction occurs. Also, no shrinkage or bleeding of water occurs with the cement glass. This solidification system was tested in an actual size pilot plant handling 200-lb drums, where it remained voidless up to 90 "C. This matrix showed high adsorption capabilities for strontium and cesium. The cement glass waste form exhibited weight changes of 0.3 percent and size changes of 0.1 percent during a freeze/thaw test, and the elasticity coefficient satisfies American Society for Testing and Materials (ASTM) standards.

(9) Equipment. Since the cementation process is for nuclear waste immobilization and reduction of permeability, the equipment to be used is a major consideration because it will become contaminated in the treatment process. If the waste is not solid, but is soil, sludge, or liquid, the mixing of the waste and cement is very important to the effectiveness of the final waste form. This mixing can be accomplished in several ways, but optimizing the use of equipment should be considered in choosing the mixing method. In the design of the process, the engineer should pay careful attention to the choice of scales and meters. Reagants and additives should be properly stored, or they will lose their useful qualities.

(10) In-drum mixing. The waste can be mixed in-drum (as shown in Figure 8-13) by inserting a mixer blade into the drum or by physically tumbling the sealed drum. In-drum mixing is advantageous because there are fewer equipment parts that become contaminated and the system is very easy to maintain. The disadvantages are that the cement and waste must be mixed drum by drum and care must be taken to blend the mixture well enough to ensure a proper final waste form, or grout-waste mixture.

(11) In-line mixing. The waste can also be mixed in-line (as shown in Figure 8-14) by feeding the waste and grout into a mixer, and then feeding the mixture or blend from the mixer into the drum. In-line mixers have the advantages of ease of cleaning, higher throughput, and the capacity to prepare composites of different sizes. This process has the disadvantages of requiring more equipment and having greater maintenance problems.

(12) Water/cement/waste ratios. Waste to cement and water ratios are best determined by treatability studies because each waste will vary in composition. Literature indicates that the success of a solidification process must be verified by bench scale tests, due to the possibility of unanticipated interference between the waste and the solidification media. Cement usually has a waste loading factor of approximately 50 percent. (Only 50 percent of the final volume is waste.)

(13) Advantages and disadvantages. Advantages and disadvantages of cement solidification are presented in Table 8-17. More detailed discussion of each item is presented in the following paragraphs.

(14) Advantages. Cementation has many advantages as an immobilization process for radioactive wastes. These include:
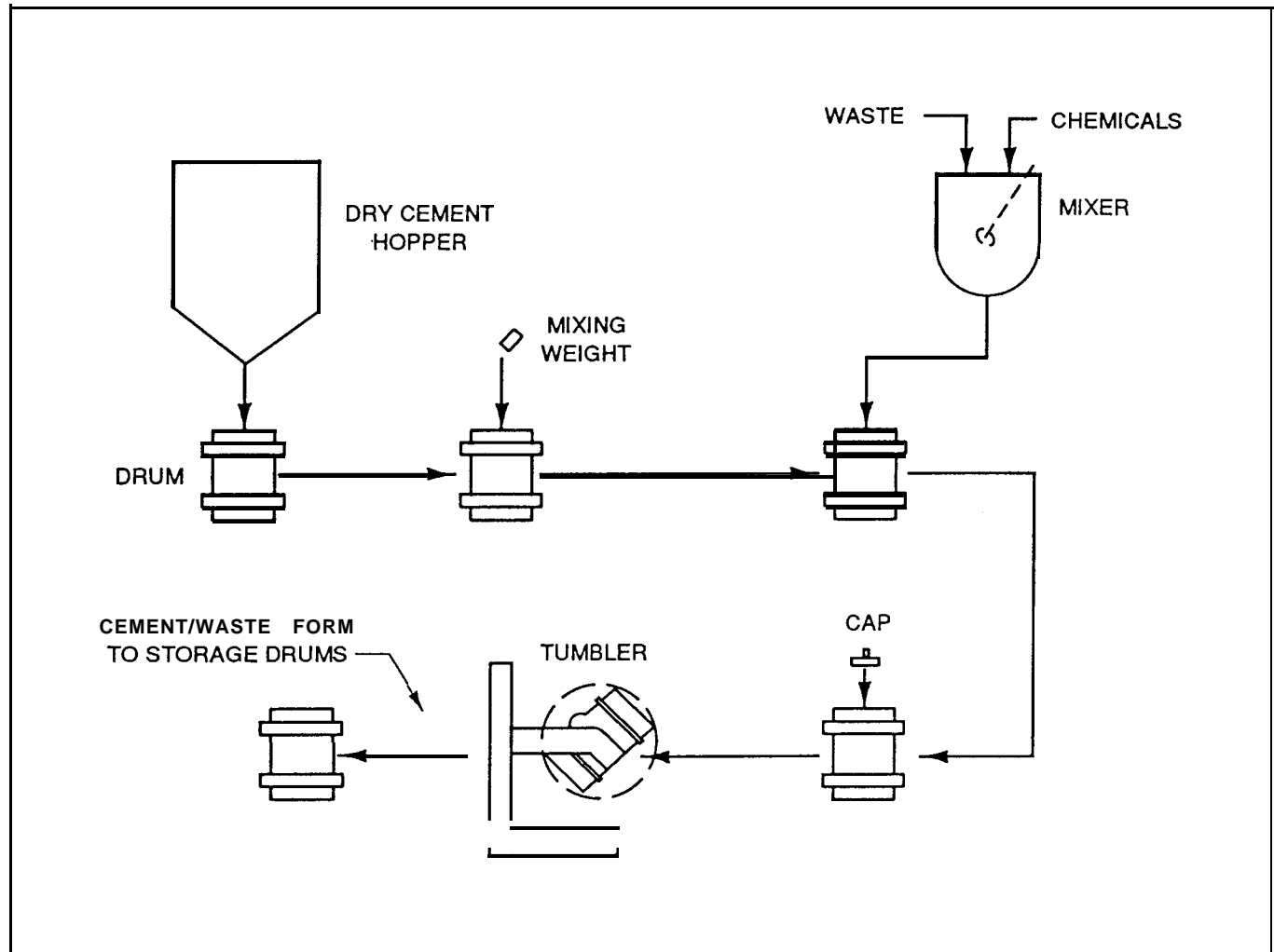
(a) It is inexpensive.

Figure 8-13. Example of in-drum mixing process

(b) Solidified waste will normally be structurally sound and can withstand the pressures imposed by the overburden in disposal trenches.

(c) Solidified waste will normally have a low permeability, which can be improved with the addition of polymers.

(d) Dewatering is not a necessary pretreatment, and additives such as sorbents can be included to further stabilize the waste form.

(e) Materials and equipment are easy to find and remote-control equipment can be obtained if necessary.

(f) Plasticized coatings can be used on the exterior of the waste-grout mixture to further protect against liquid intrusion.

(g) Hydraulic cement costs on the order of $0.10/lb or less.

(15) Disadvantages. Cementation also has several disadvantages, which must be considered when choosing a treatment method. They are as follows:

(a) Waste can leach from the matrix because it is not chemically bound. The addition of sorbents and emulsifiers often lowers the leaching losses from the treated wastes.

(b) The solidified waste form increases the volume by a factor of 1.3 to 1.5, which will increase disposal costs based on volume. However, treatment systems employing volume reduction of the waste will concentrate the activity, which will in turn increase disposal costs based on activity.
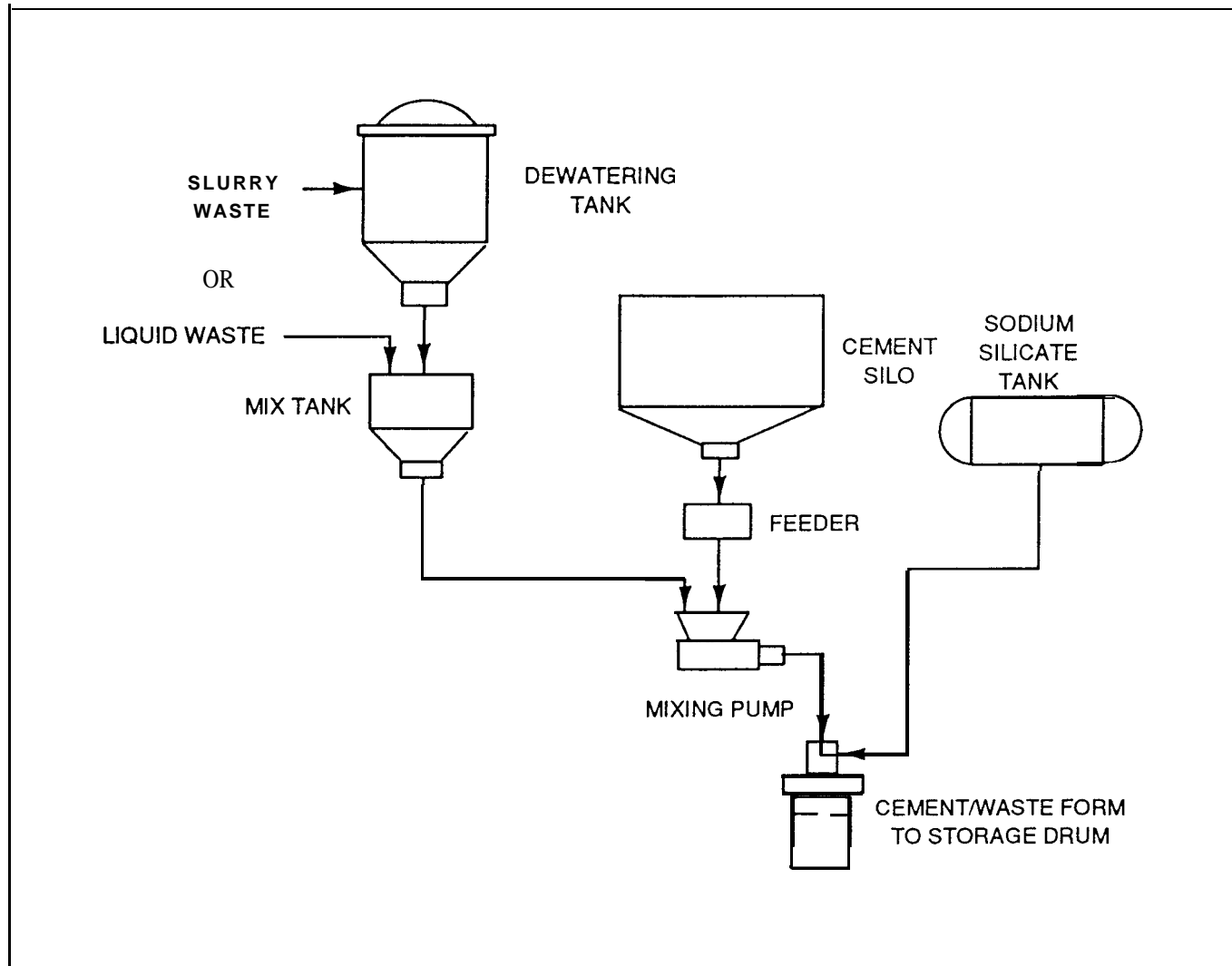
Figure 8-14. Example of in-line mixing process (Source: IAEA 1983)

(c) Solidified waste can be adversely affected by the temperature and pH inside the disposal trenches, causing it to crack or crumble.

(d) Waste constituents shown in Table 8-18 may adversely affect cement solidification. Pretreatment may be effective in preventing problems for many of these constituents.

(e) If ammonium ions are present in the waste, the high pH of the cement-grout mixture may cause ammonia gas to be formed.

(f) Exothermic reactions may occur if the cement-grout or concrete is mixed with highly acidic wastes.

(g) Some metals are very soluble in alkaline environments, which would create a leachate problem.

(16) Treatability studies. To be assured that cementation is a viable treatment choice, a thorough waste analysis and sample testing (treatability study) should be conducted. Although bench-scale studies will yield such information, a pilot-scale study of the process will provide more accurate, realistic testing and information to predict the feasibility of the proposed solidification/stabilization treatment process. Treatability studies are further discussed in Chapter 13. Waste characterization is discussed in Chapter 6.

(17) Incompatible substances. Table 8-18 lists waste constituents that may cause problems with cement

Table 8-17
Advantages and Disadvantages of Cement Solidification

Advantages	Disadvantages
Inexpensive	Wastes can leach from matrix
Structurally sound	Volume increase
Can withstand high pressures	Temperature and pH can degrade end product
Low permeability	Many constituents may adversely affect cementation
Dewatering is not necessarily a pretreatment	Ammonia and hydrogen gases can be produced
Easy to find equipment	Exothermic reactions may occur
Remote-control equipment available	Metals may leach
Plasticized coatings can be used to reduce leaching	

Table 8-18
List of Waste Constituents That May Cause Problems with Cement Solidification

Potential Problem Constituents Which May Be Expected in the Waste Stream	
Inorganic Constituents	**Organic Constituents-Aqueous Solutions**
Berates[1]	Organic acids'
Phosphates[1]	Formic acid (and formates)
Lead salts[2]	
Zinc salts	"Chelates"[1,3]
Ammonia and Ammonium salts	Oxalic acid (and oxaltes)
Ferric salts	Citric acid (and citrates)
"Oxidizing agents"[1]	Picolinic acid (and picolinates)
(often proprietary)	EDTA (and its salts)
Permanganates[1]	NTA (and its salts)
Chromates[2]	
Nitrates[1]	"Decon solutions'"
Sulfates[1]	Soaps and detergents'
	Organic Constituents-Oily Wastes
	Benzene[1,2]
	Toluene[1,2]
	Hexane[1]
	Miscellaneous hydrocarbons
	Vegetable oil additives

Potential Problem Constituents That May Be Avoided By Housekeeping or Pretreatment'	
Generic Problem Constituents	**Specific Problem Constituents-Organic**[5]
Oil[1] and grease	Acetone[1,2]
"Aromatic oils"[1]	Methyl ethyl ketone[2]
"Organic solvents"[1,2]	Trichloroethane[2]
Dry-cleaning solvents[1,2]	Trichlorotrifluoroethane[2]
"Industrial cleaners"[1,2]	Xylene[2]
Paint thinners[1,2]	Dichlorobenzene[2]
"Decon solutions"[1]	
Soaps and detergents[1]	
	Specific Problem Constituents-Inorganic
	Sodium hypochlorite[1]

[1] These constituents have been specifically identified by vendors as having the potential to cause problems with cement solidification of low-level wastes.
[2] The presence of these constituents may result in the generation of mixed wastes. The Environmental Protection Agency should be contacted for more information.
[3] All of these chelating agents could be identified as "organic acids."
[4] Good housekeeping and pretreatment could also be effective in preventing problems with cement solidification for many of the constituents listed in the top list.
[5] These specific constituents also fall into several of the "generic" problem constituents "categories" listed at the left.

Source: NRC 1991

solidification. If sodium salts of arsenate, borate, phosphate, or codate, sulfide salts of magnesium, tin, zinc, copper, or lead, organics, some silts and clays of extremely small particle size, coal, or lignite are present in significant quantities, the waste form will neither set, cure, nor endure sufficiently.

(18) Post-treatment requirements. The waste form must meet certain post-treatment performance requirements, and quality assurance/quality control checks must be followed. These are discussed in detail in Chapter 9.

b. Thermoplastics.

(1) Introduction. Thermoplastics can also be used as matrices for immobilizing radioactive wastes. This process is commonly called "thermoplastic microencapsulation." The most common thermoplastic used is bitumen, which is also known as asphalt. Polyethylene and polypropylene are examples of other thermoplastics that can be used. This technique differs from cementation in that the bitumen must be heated to be mixed with the waste, and the waste must either be dried before treatment or the water must be driven off during the process. The same type of containers are used as for cementation (see Chapter 10). Because of the nature of encapsulation, waste forms containing up to 50 percent by weight of solid waste can be achieved. The literature also reports waste loading factors of 45-60 percent.

(2) Modified sulphur cement.   Modified sulphur cement, also called sulphur polymer cement, has emerged as another alternative to hydraulic cement and bitumen for the solidification of radioactive wastes.   Sulphur cement is produced in excess of 5 million tons (4.5 billion kg) per year by the U.S. Bureau of Mines to make use of by-product sulphur.   It is made by reacting elemental sulfur with a total of 5 wt % hydrocarbon modifiers consisting of equal parts of dicyclopentadiene and oligomers of cyclopentadiene. Modified sulphur cement is a thermoplastic that begins melting at 110 "C, has an optimum pour temperature of 135 "C, and a maximum safe operational mixing and pouring temperature of 150 ℃.   The modified sulphur cement, like bitumen, must be combined with a dry waste form and cooled to produce a solid waste form. A strong, durable waste form is produced at a cost of $0.37/kg ($0.17/lb). The sulphur cement is stable and resistant to extremely harsh environments and attack by most corrosive acids and salts. A chemical reaction is not required for solidification, as in hydraulic cement. Its mechanical strengths are approximately double those of most hydraulic cements, and full strength is attained within hours rather than weeks as for hydraulic cement. Modified sulphur cement has the same density as portland cement if identical waste is used. Linear shrinkage is slightly greater than portland cement.

(3) Applications of modified suphur cement. Modified sulphur cement has been used at Brookhaven National Laboratory for the solidification of LLRWS containing sodium sulfate salts, boric acid salts, and incinerator bottom ash.   It has also been used for the treatment of a mixed waste containing incinerator fly ash. Modified sulphur cement offers a valuable operational advantage in that the mixer does not have to be emptied and cleaned upon completion of a pour.   Instead, the modified sulphur cement and waste mixture can be kept molten until a later time or it can harden and be remelted later. Brookhaven National Lab recommends that sulphur cement should not be used to stabilize nitrate salts and other oxidizers because the mix could become reactive. Dried ion exchange resins and expanding clays pick up moisture during the immersion test, which causes them to swell and rupture the cement.   Thus, these substances should not be solidified with modified sulphur cement either.

(4) Batch and continuous processes.   There are several different microencapsulation processes involving varying ways of mixing and drying.   They can be classified into batch processes and continuous processes. The following descriptions are from Technical Reports

Series (TRS) 222, p. 59 (International Atomic Energy Agency (IAEA) 1983).

(5) Batch process with evaporation. For liquid wastes and sludges, a batch-bitumenization process with evaporation can be used (Figure 8-15). A volume of waste is continuously mixed with a volume of molten bitumen externally heated to 200 ℃.   The water evaporates and the solids are mixed with the bitumen. The mixture is then poured into containers and cooled. Local overheating and formation of incrustation may occur if the temperature is not maintained within a narrow interval.
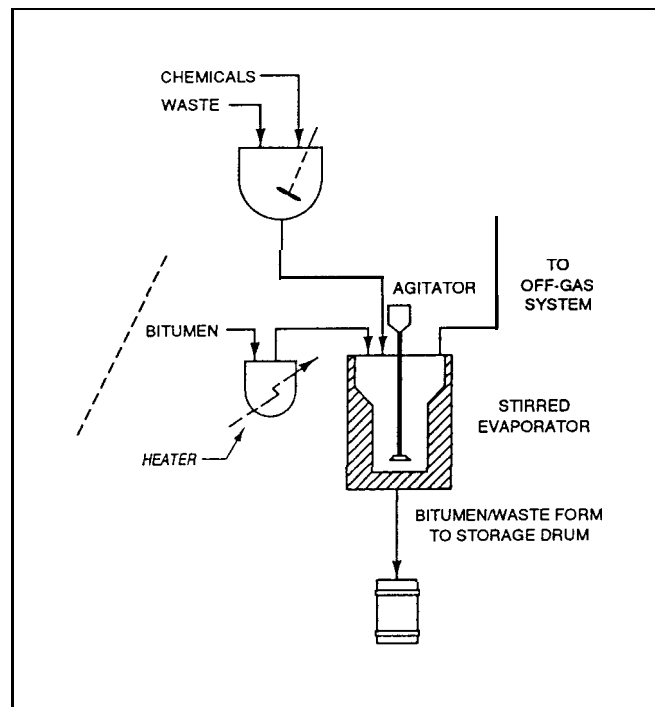

Figure 8-15. Stirred evaporator batch process

(6) Batch process without evaporation.   Batch-bitumenization process without evaporation (Figure 8-16) can also be used, but the waste must be dried before treatment.   A steam-heated dryer is used which measures the correct amount of waste and feeds it into the mixer. The waste is mixed with bitumen at 130 'C and then released into containers to cool. A steam collection and treatment system must be included to catch and filter the steam and off-gases.   This system is simpler than the batch process with evaporation, because the evaporation and mixing steps are separated. Thus, different power demands do not arise which avoids overheating and incrustation formation.
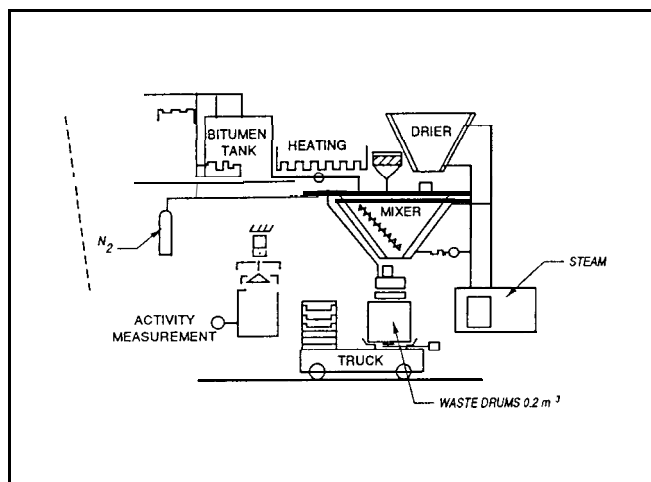
Figure 8-16. Batch process without evaporation (Source: IAEA 1983)

Figure 8-18. Two-step extrusion process (Source: IAEA 1983)

(7) Single-step continuous extrusion process. The single-step extrusion process (Figure 8-17) can treat a variety of wastes, including liquids, sludges, and particulate. The waste and melted bitumen are continuously fed into a twin-screw extruder that is heated. As the mixture is blended in the extruder, the water evaporates into steam domes. The mixture is then poured into drums located on a rotating platform. The continuous operation of this system is desirable. However, an off-gas collection system is required. Also, the process parameters must be carefully controlled, which requires adequate instrumentation and skilled operators.
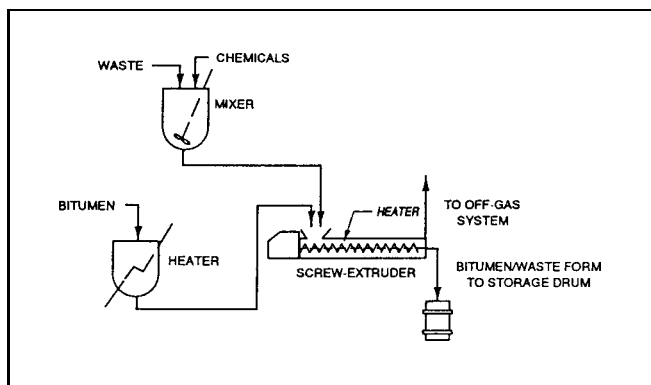
the waste went from containing 50 percent water to 8 percent water. In the second extruder, the remaining water is evaporated, and the waste mixture is released into a container. In the example referenced, the final mixture contained 0.5 percent water. The two-step extrusion process has a higher capacity than the one-step process, but the equipment and maintenance costs are much higher.

(9) Advantages and disadvantages. Advantages and disadvantages of bitumen solidification are presented in Table 8-19. A more detailed discussion is presented in the following paragraphs.

Figure 8-17. Screw extruder evaporation process

(8) Two-step continuous extrusion process. A two-step extrusion process (Figure 8-18) has been developed which is very similar to the one-step process. Here, the waste passes through two screw extruders. In the first, a great deal of the water is pressed off. In one example,
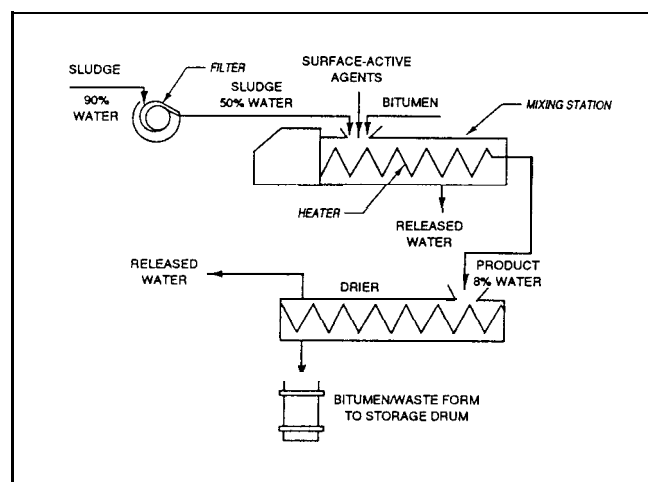
Advantages and Disadvantages of Bitumen Solidification	
Advantages	**Disadvantages**
Can immobilize very soluble, toxic materials	Costs will be considerably higher than cementation
Bitumen is insoluble in water	Waste form must rely on a container for support
Leaching potential below cementation	Wastes must be dewatered
Microorganisms have little effect	Volume and weight increase
Volume increase is not as drastic as cementation	Bitumen is combustible
Wastes are retrievable	Can be damaged by radiation
Remote control equipment available	Softens at high temperatures
Plasticized coatings can be used	Tendency to swell

(10) Advantages.   Bitumenization is a widely used treatment for low-level and mixed radioactive wastes and has many advantages. They are as follows:

(a) Bitumen offers a strong internal matrix that can solidify and immobilize very soluble, toxic materials.

(b) The waste form is liquid-free and bitumen is insoluble in water, which reduces the leaching potential below that of cementation.

(c) Microorganisms and groundwater have little effect on the treated wastes.

(d) Since the waste is dried, the initial and final weights and volumes will not be as drastically different as with cementation. This saves on disposal costs.

(e) The wastes are retrievable.

(f) Remote control equipment can be obtained if needed.

(g) Plasticized coatings can be used on the exterior of the waste form to further protect against liquid intrusion.

(11) Disadvantages.   The following are important disadvantages to consider before selecting microencapsulation as a treatment alternative.

(a) Equipment, labor, and power costs will be considerably higher with bitumenization than with cementation.

(b) The waste form must rely on a container for support in the disposal trench, because the bitumen is solid but not rigid.

(c) The waste must be dewatered before or during treatment.

(d) The weight and volume of the final waste form is large.   However, because the waste is dewatered, the difference between the initial and final weights is not as great as with cementation.

(e) The bitumen is combustible, although not easily flammable.

(f) The bitumen may be damaged by radiation.

(g) The bitumen softens at temperatures greater than 100 $^{\circ}$F.

(h) The bitumen has a tendency to swell.

(12) Incompatible substances. Waste-bitumen interactions are just as important as waste-cement interactions. Many substances are incompatible with bitumenization. Solvents and greases will cause the waste form to be too elastic. The treated waste will crack and split if chemicals that react with the organic portion of the matrix are included, such as nitrate, chlorate, and perchlorate salts. Borate salts cause the mixture to solidify too quickly, which could be very damaging to equipment. Dehydrated salts may rehydrate out of solidification if contact is made with water.   Substances, such as solid hydrocarbons, sulfur, perchlorates, or nitrates, which combust at high temperatures, will bum or explode at the 130 $^{\circ}$C to 200 $^{\circ}$C used during the microencapsulation process.

(13) Temperature effects. At temperatures less than O $^{\circ}$C, bitumen loses its plastic properties and becomes more glass-like.   This temperature is dependent on the type of bitumen. A range of +5 $^{\circ}$C to -10 $^{\circ}$C is reported in the literature.

(14) Radiation effects. The stability of bitumen with respect to radiation is of primary importance. Dose rate and total absorbed dose are the main factors influencing the radiation stability of the bitumen.   The type of bitumen plays only a minor role. A total absorbed dose of 10^{8} to 10^{9} rad is commonly reported for the radiation resistance of bitumen waste forms.

c. Polymers.

(1) Introduction.   Polymer solidification is another viable treatment for   radioactive wastes.   Urea-formaldehyde,   polyacrylamide,   and polyester are examples of polymers that can be used in this process. The waste, polymer, and a catalyst are mixed together in either an in-line mixer or in-drum system.   The polymeric processes do not really solidify the wastes; the long chained molecules of the organic polymer are linked together to form a porous sponge that 'traps' the waste.

(2) Characteristics. Polymer processes are generally conducted at temperatures between 20 "C and 60 'C. Depending upon the polymer, the waste may or may not have to be dewatered before being treated.   Also

polymer-dependent, the waste mixture may form a rock-hard solid or a more flexible mass.

(3) Urea-formaldehyde process. Urea-formaldehyde (UF) was once the most common polymer process, but has been replaced by other polymers because of several problems. The UF process is performed at a pH of 1.5, which is much too low for use in carbon steel drums. If the waste contained any liquid, the waste form would "weep" for months, necessitating the use of additional absorbents. Polyethylene and polyacrylamide have replaced the UF process in most instances.

(4) Costs. Polymer grout can fill more than 97 percent of the void space in a waste material, which makes the waste more solid and less permeable. Polymers are, in general, much more expensive than cement grout. Thus, the amount of voids and the type of void spacing in the waste can determine if the polymer grout process will be cost-effective. Compaction and dewatering also impact the effectiveness of the process. The effect of radiation on the compressive strength of polymers is not great, even at $>10^9$ rad dose.

(5) Advantages and disadvantages. Advantages and disadvantages of polymer solidification are given in Table 8-20. A more detailed discussion is given in the following paragraphs.

Table 8-20
Advantages and Disadvantages of Polymer Solidification

Advantages	Disadvantages
Can solidify a wider range of wastes	Wastes would be released if the polymer failed
Reduces permeability of waste Many polymers do not require heating	Expensive Unknown response to environmental stresses
Short curing times Much less weight increase than for cement or bitumen	Water may affect waste form Container needed for support
	Some polymers are too acidic for a carbon steel drum
	Temperatures can adversely affect waste form
	Skilled labor needed
	Potential for radiation damage

(6) Advantages. Listed below are the advantages for using polymerization.

(a) Polymers can solidify a wider range of wastes than other solidification processes, such as organic wastes.

(b) The waste material is less permeable than before polymerization.

(c) Many polymers do not require heating.

(d) Curing times are usually much less than for cementation or bitumenization because of the work of the catalyst.

(e) The polymer matrix is much lighter than cement or bitumen so the final waste form will be much lighter, which might reduce transportation costs. Volumes will not significantly change.

(7) Disadvantages. The long-term effectiveness of many of the polymers has not been determined, so extra care must be taken when selecting polymerization as a treatment alternative. The following are disadvantages to consider:

(a) The process is expensive.

(b) If the polymer failed, the waste contaminants would be released.

(c) Little information is known about how polymers respond to environmental stresses over time.

(d) Residual water may have a significant effect on the physical integrity of the waste form.

(e) The waste form will most likely need to be held and supported by a container.

(f) Some polymers, such as UF, are too acidic to be in a normal carbon steel drum.

(g) Ground and air temperatures can adversely affect the treated waste.

(h) Skilled labor is needed to operate the treatment system.

(i) The polymer matrix may be damaged by radiation.

(8) Treatability tests. Waste analysis is very important when using polymers. Only polymers that have been extensively tested and proven to be compatible and reliable should be considered.

d. Vitrification.

(1) Introduction. Vitrification, the process of converting materials into a glass or glass-like substance, is increasingly being considered for treating various wastes. The recent modification to the tri-party agreement at Hanford stipulates that LLRW from single-shell tanks will be vitrified rather than being stabilized by cementation. The following information is primarily condensed from the EPA handbook "Vitrification technologies for treatment of hazardous and radioactive waste" (EPA 1992a). Vitrification is conceptually attractive because of the potential durability of the product and the flexibility of the process in treating a wide variety of waste streams and contaminants. These characteristics make vitrification the focal point of treatment systems for high-level radioactive waste and an attractive alternative for low-level radioactive waste. Vitrification may proceed in situ or ex situ.

(2) In situ vitrification (ISV). In situ vitrification is the process of vitrifying the waste as it is present in the environment. An advantage of ISV is that it proceeds in situ without requiring that the material be removed prior to treatment. With radionuclides or dispersible volatile compounds, this may be a significant advantage. Furthermore, the product remains buried underground and onsite, thus limiting liability by keeping the waste product onsite. In situ processes typically operate between 1,600-2,000 $^{\circ}$C.

(3) Ex situ vitrification. Ex situ vitrification involves the removal of the contaminated material from the ground and processing the displaced material either onsite or offsite. The advantages of ex situ over in situ lie primarily in the increased amount of control that can be exerted during processing. This control extends to feed composition and melt conditions and this in turn allows for greater control of product characteristics and allows product examination. For processes aimed at a specific waste stream, control is increased because of the relative homogeneity of the waste stream. Secondly, ex situ vitrification allows greater control over the combustion of non-pyrolyzed organics escaping from the melt. For these processes, the environments in the molten glass melt and in the secondary combustion area can be more easily regulated to facilitate efficient organic destruction.

Ex situ processes typically operate between 1,000 and 1,600 "C. The main disadvantages of ex situ vitrification are the increased volume of the vitrified waste and the increased cost and worker exposure involved in the excavation and handling of the removed materials.

(4) Glass composition. Glass is a rigid, noncrystalline material of relatively low porosity, often composed primarily of silica, alumina, and oxides of alkali and alkaline earth elements. While phosphate, sulfide, and oxynitride glasses are also important glass types, most glasses used in waste immobilization are silicate glasses. Inorganic waste constituents are immobilized in vitrification processes by chemical bonding or encapsulation within the glass matrix.

(5) Alkali attack. Vitreous materials are often thought of as being "inert," which is somewhat justified since these materials exhibit high corrosion resistance compared with many other materials. It is important to note, however, that all vitrified products are chemically reactive to some degree. There are two major forms of chemical attack on vitrified materials: alkali and acid. Alkali attack begins by hydration of the silica network and may proceed to dissolution of the matrix material. In pure silica glass, the matrix dissolution process can be described by the following equation:

$$2NaOH + SiO_2 \rightarrow Na_2SiO_3 + H_2O \qquad (8\text{-}1)$$
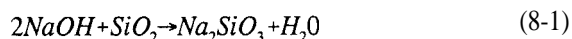
The alkali silicate (Na_2SiO_3 in the example shown) is water soluble, so as the silica network is attacked and dissolved, the other constituents in the vitrified material are released. The rate of alkali attack is generally linear with time; however, the rate can change if soluble materials accumulate in solution, or if insoluble reaction products adhere to the material's surface, blocking the reaction. Alkali attack is highly pH dependent. The rate of attack generally increases by a factor of 2 to 3 for each pH unit increase. Temperature also has an influence on the rate of alkali attack. The rate of attack increases by a factor of 2 to 2.5 for each 10 $^{\circ}$C temperature rise. Many chelating compounds attack glasses at a rate comparable to that of strong alkali. Citrate, gluconate, oxalate, tartrate, ethylene diamine tetra-acetic acid (EDTA), and malate all attack glass in alkaline solution. Alkaline phosphate and acetate also attack glass readily. Hydrofluoric acid has a unique ability to dissolve silicate glasses, forming a solution of alkali fluorides and silicon fluorides.

(6) Acid attack. While alkali attack leads to surface dissolution of the vitreous material, acid attack is an ion exchange process which involves the exchange of hydronium ions in solution for ionically bonded elements in the vitreous network. The acid attack reaction rate increases by a factor of 1.5 to 2 for each 10 $^{\circ}$C temperature rise. Depending on the composition of the vitrified material, especially its silica content, the pH of the leaching solution influences the rate of acid attack but not as much as in alkali attack.

(7) Feed composition. Composition of the incoming feed can have enormous effects on product durability and processing parameters. Table 8-21 displays some of the effects of various inorganic oxides on processing and glass durability. Modification of the waste stream through additives and/or material removal can have dramatic impacts on processing and product characteristics. However, as Table 8-21 shows, most additives have both desired and undesired effects. Therefore, modification of the feed will often involve compromises based on treatment goals, processing limitations, and waste character.

(8) Waste loading. Increased waste loading does not necessarily increase product leachability. Research on borosilicate glass for the immobilization of nuclear waste has indicated that glass leachability is reduced as the waste loading increases from O wt % to 35 wt %, with only small changes in leachability as the waste loading increases from 35 wt % to 50 wt %. Thus, the amount of waste immobilized by borosilicate glass may not be limited by product durability but by processing considerations.

(9) Joule heating.

(a) In joule heating, an electric current flows through the material. As the material internally resists the current, the current loses power and transfers heat energy to the material. The dissipated power is predicted by Joule's Law. With increased electrical resistance, if current can be maintained, additional power is dissipated and the material heats more rapidly. However, unless the voltage is increased, an increase in resistance will also decrease current. This is predicted by Ohm's Law. Ohm's Law explains why materials with low resistivity are often heated at low voltages (5 to 48 V) in nonvitrification processes. However, soils and other materials heated by joule heating are frequently quite resistant and require higher voltages.

(b) Characteristics of the molten glass place mechanical constraints on the design of a joule heating system. For example, the conductivity of molten glass is ionic; therefore, an alternating current (AC) must be used to avoid the risk of electrolysis, anodization of electrodes, and the depletion of charge carriers. Electrodes must withstand corrosion from the molten glass bath, offer adequate mechanical strength at high temperatures, and have low resistivity. The commercial glass industry generally uses graphite and molybdenum for electrodes. The position of the electrodes in the furnace controls the buildup of convection currents in the melt and, subsequently, homogeneity in the melt. Joule heating can be carried out both ex situ and in situ.

(c) Ex situ joule heating involves feeding the contaminated material into a melter. Some melters are much like electric glass furnaces used to manufacture glass products. Such melters receive waste materials and glass batch chemicals directly on the surface of a molten glass bath. Most melting occurs at the waste/molten glass interface. As waste is heated, volatiles may be released and organics are either pyrolyzed (in an oxygen-poor environment), or oxidized (in an oxygen-rich environment). Off-gas treatment is required to minimize air emission, Figure 8-19 shows a process flow-sheet for a typical joule-heated ceramic melter. Processing problems which may occur in electric melters are discussed in the EPA handbook titled "Vitrification technologies for treatment of hazardous and radioactive waste" (EPA 1992a). These problems can generally be controlled by feed modifications.

(d) The process that is commonly referred to as ISV is more specifically in situ joule heating. ISV was developed by Battelle at Pacific Northwest Laboratory for the U.S. DOE. ISV has been used to treat a variety of hazardous chemical, radioactive, and mixed wastes. ISV converts contaminated soil and other substrates into a stable glass and crystalline product. Figure 8-20 depicts the process.

(e) The Electrode Feed System (EFS) inserts a square array of four graphite electrodes into the contaminated site. This mechanism allows the electrodes to sink to increasingly greater depths as the molten glass increases in volume. Processing continues until the desired treatment level is reached, or until a process-limiting depth is reached. If processing difficulties are

Table 8-21
Effects of Waste-Glass Components on Processing and Product Performance

Frit Components	Processing	Product Performance
SiO_2	Increases viscosity greatly; Reduces waste solubility	Increases durability
B_2O_3	Reduces viscosity; increases waste solubility	Increases durability in low amounts, reduces in large amounts
Na_2O	Reduces viscosity and resistivity; increases waste volubility	Reduces durability
Li_2O	Same as Na_2O, but greater effect; increases tendency to devitrify	Reduces durability, but less than Na_2O
K_2O	Same as Na_2O, decreases tendency to devitrify	Reduces durability more than Na_2O
CaO	Increases, then reduces, viscosity and waste solubility	Increases, then reduces, durability
MgO	Is same as CaO; reduces tendency to vitrify	Is same as CaO, but more likely to decrease durability
TiO_2	Reduces viscosity slightly; increases, then reduces, waste volubility; increases tendency to devitrify	Increases durability
ZrO_2, La_2O_3	Reduces waste solubility	Increases durability greatly

| Waste Components	Processing	Product Performance
Al_2O_3	Increases viscosity and has tendency to devitrify	Increases durability
Fe_2O_3	Reduces viscosity; is hard to dissolve	Increases durability
U_3O_8	Reduces tendency to devitrify	Reduces durability
NiO	Is hard to dissolve; increases tendency to devitrify	Reduces durability
MnO	Is hard to dissolve	Increases durability
Zeolite	Is slow to dissolve; produces foam	Increases durability
Sulfate	Is an antifoam, melting aid; increases corrosion of processing equipment	Too much causes foam or formation of soluble second phase

Source: EPA 1992a
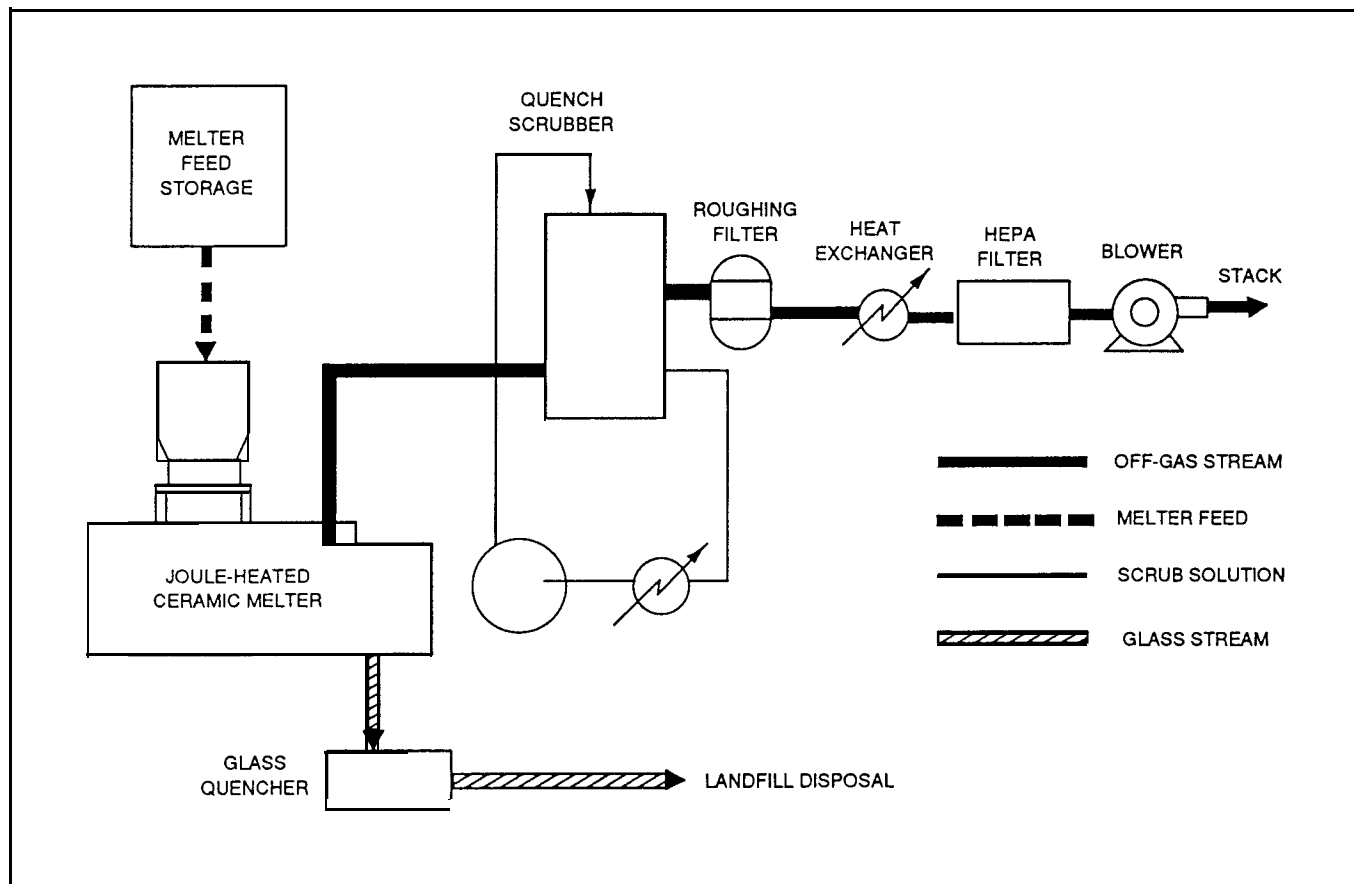
Figure 8-19. Typical JHCM process flowsheet (Source: EPA 1992a)

encountered, then EFS can "grasp" the electrodes and thus prevent their downward movement until the difficulty is addressed. Previously, ISV required insertion of the electrodes into boreholes prior to vitrification.

(f) Because soil is not electrically conductive when moisture has been driven off, a conductive mixture of flaked graphite and glass frit is placed between the pairs of electrodes as a starter path. An electrical potential is applied to the electrodes to establish an electrical current in the starter path. The resultant power heats the starter path and surrounding soil to 2,000 °C, well above initial soil-melting temperatures of 1,100 °C to 1,400 °C. The graphite starter path is eventually consumed by oxidation and the current is transferred to the molten soil, which is electrically conductive when molten. As the molten or vitrified zone grows, it incorporates radionucides and nonvolatile hazardous elements, such as heavy metals, into the melt and pyrolyzes organic components. The pyrolized by-products migrate to the surface of the vitrified zone where they combust in the presence of oxygen. A hood placed over the vitrified area directs the gaseous effluents to an off-gas treatment system.

(g) Attempts to reduce costs by utilizing a fabric hood were not successful. Fabric hoods have caught fire twice in ISV tests, once during a Pacific Northwest Laboratory (PNL) test, and once during a Geosafe test. Both fires started when molten material splashed on the hoods . The hoods used at the time of the fires were fabric hoods coated with heat-resistant sealants. Since these fires, both PNL and Geosafe have reverted to previous steel hood designs.

(h) As the melt grows downward and outward, power is maintained at sufficient levels to overcome heat losses from the surface and to the surrounding soil. Generally, the melt grows outward beyond the electrodes to a distance equal to about half of the spacing of the electrodes. The molten zone is circular and somewhat flattened. The tendency to flatten increases as melt size increases.
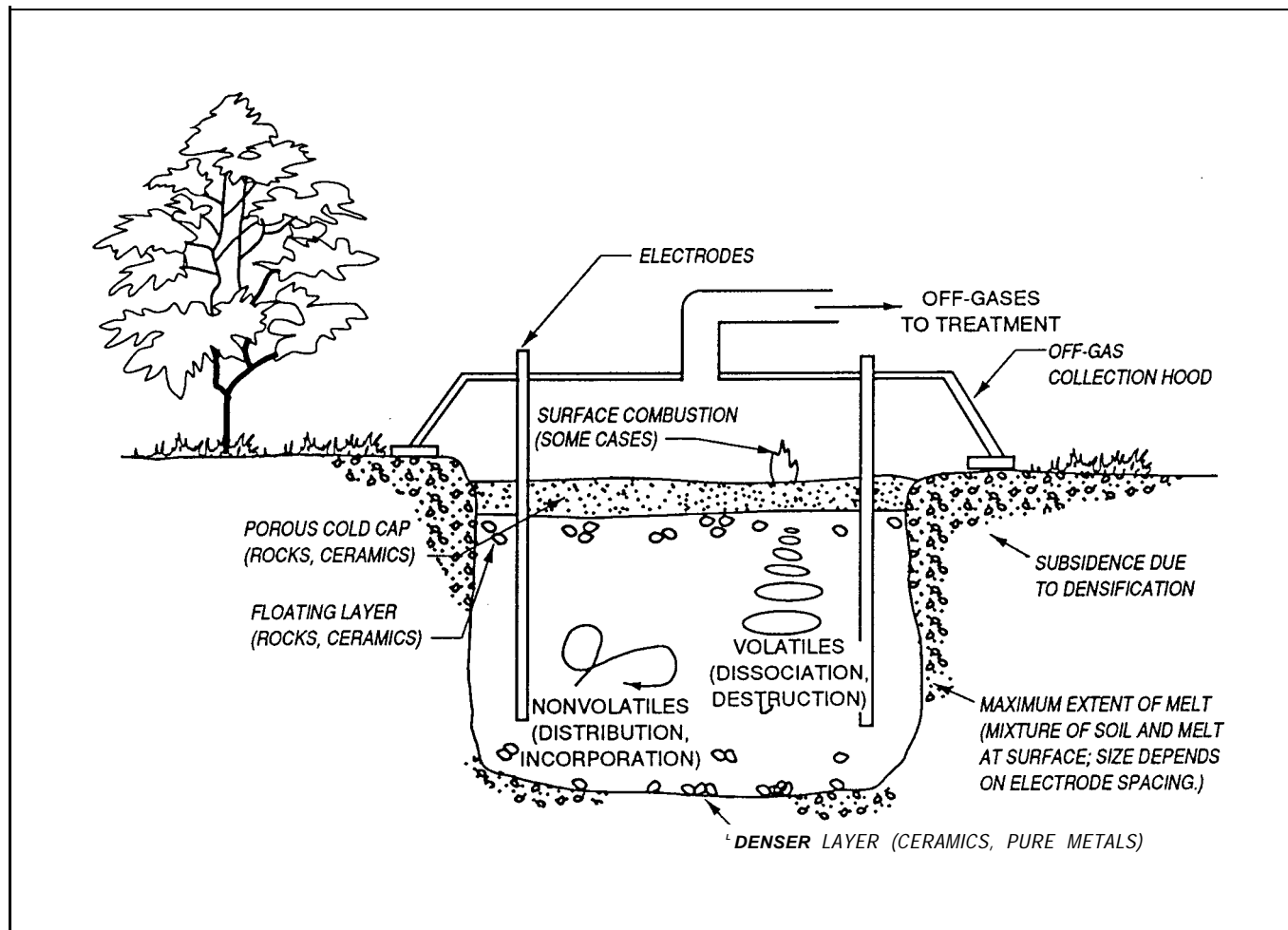
Figure 8-20. Schematic of ISV (Source: EPA 1992a)

(i) In order to control the amperage during ISV processing, operators use a power transformer with multiple voltage taps. At start-up, the ISV process requires high voltage (up to 4,000 V) to overcome the resistance of the soil. Current is relatively low (400 A) at this time. As the melt progresses and resistance decreases, voltage is decreased (down to 400 V by the end of processing) to compensate for the decreased resistance of the molten glass and the resulting increase in current (up to 4,000 A by the end of processing). Processing continues until heat loss from the melt approaches energy delivered to the soil via the electrodes, or until power to the electrodes is shut off.

(j) The normal processing rate for the large-scale system is 3 to 5 tons/hr (2,700 to 4,500 kg/hr). The maximum depth demonstrated thus far has been 5 m by PNL and 5.8 m by Geosafe. The average processing operation lasts about 150 to 200 hr, depending on the depth and electrode spacing.

(k) ISV processing is termed "in situ" when the soils are processed where they presently exist. Placing soil in a trench or container for treatment is termed "staged" processing. For example, a staged application may involve consolidating contaminated soil by removing the soil and placing it in a trench. The filled trench could then be vitrified. Typically, staged application would be most effective where the contaminants are widely distributed in the top few feet of the site. Because ISV is a batch process, it may not be cost-effective to move the hood from setting to setting to vitrify only the top few feet of the contaminated material.

(10) Plasma heating.

(a) Plasma heating is an electrical heating process which relies on the conversion of a gas into a plasma through the application of energy by an electric arc. Plasma heating offers high operating temperatures and high power densities. Unlike joule heating vitrification, which grew out of the glass-making industry, plasma heating vitrification has grown out of the speciality metals industry.

(b) A plasma is an ionized gas. The ionized particles make plasma an excellent electrical conductor. There are two types of plasmas: plasmas in which the degree of ionization is close to unity and plasmas which are only partially ionized. The first type occurs in thermonuclear fusion and is found in the sun. In partially ionized plasmas, the degree of ionization varies from 2 to 50 percent. The temperatures of partially ionized plasmas vary between 2,000 °K and 5,000 °K. Partially ionized plasmas are used in industrial applications.

(c) Plasma is commonly created by passing a gas through an electrical arc. The arc can be generated by direct current (DC) or alternating current (AC). With a DC arc, the cathode generally consists of tungsten and the anode generally consists of copper. The anode also typically functions as a nozzle directing the plasma. In contrast, in a single phase AC arc plasma generator, the electrodes act as the cathode and anode alternately, and must therefore be made of the same material.

(d) Gases used in generating a plasma arc include nitrogen, oxygen, noble gases, air, and mixtures of these gases. Electrode life is a major concern and is influenced by electrode material, the gas used, and electrical current levels. Electrode structure, gas injection method, and nozzle design help shape the plasma and determine heating efficiencies.

(e) The product is heated in one of two ways: by a non-transferred arc or by a transferred arc. A non-transferred arc uses two internal electrodes. Non-transferred arcs heat only via conduction and produce a dispersed heat that is needed for tasks such as air and gas heating and drying. A transferred arc uses the working material as one of the electrodes. Therefore, in a transferred arc application, heating occurs via convection, radiation, and electrical resistance. It is the transferred arc that is the heat source in hazardous and radioactive vitrification applications. In these applications, the plasma arc melts the material to form a molten bath from

which glass is periodically removed to form the immobilized waste product.

(f) Retech, Inc., of Ukiah, CA, has developed a plasma heating furnace called the plasma centrifugal reactor (PCR). In the PCR, prepared waste materials are fed into a rotating reactor in which a transferred-arc plasma torch is operating. The rotating reactor also serves as one electrode for the transferred arc. The plasma torch, which is capable of temperatures exceeding 10,000 °C, heats the waste material beyond the point of melting to about 1,600 °C. Centrifugal force created by the rotating reactor prevents waste and molten material from flowing out of the reactor through the bottom. The rotation of the reactor also helps to transfer heat and electrical energy evenly throughout the molten phase. Periodically, the melted material is allowed to fall into a slag chamber where it is collected in waste containers. Figure 8-21 is a schematic of a demonstration PCR; it shows the location of the electrodes and the way in which the molten glass pools due to centrifugal forces. Organics and other volatiles emitted during the plasma heating pass from the reactor chamber to a secondary combustion chamber into which an oxidizing gas is added, thus allowing for further destruction of any organics remaining in the gas phase. Resulting off-gases are then transferred to an off-gas treatment system to ensure safe air emissions. Figure 8-22 illustrates the components of a full-scale PCR.

(11) Microwave heating.

(a) Microwave heating is a form of dielectric heating. A dielectric is a material which is an electrical insulator. A dielectric becomes polarized when it is placed in an electric field. If the electric field is alternating, successive distortion of the molecules causes heating. Materials such as incinerator ash, thermal insulators, concrete, soil, and sand are mostly composed of dielectric material and can be directly melted by microwave radiation.

(b) Dielectric heating is usually classified into two subcategories on the basis of frequency ranges used: radio frequency heating using frequencies between 10 and 300 MHz, and microwave heating using frequencies between 3,000 and 30,000 MHz.

(c) The main advantage of microwave heating is that the heat is produced directly and solely in the mass of the material to be heated. Another advantage is high power density. The main disadvantage is relatively high energy
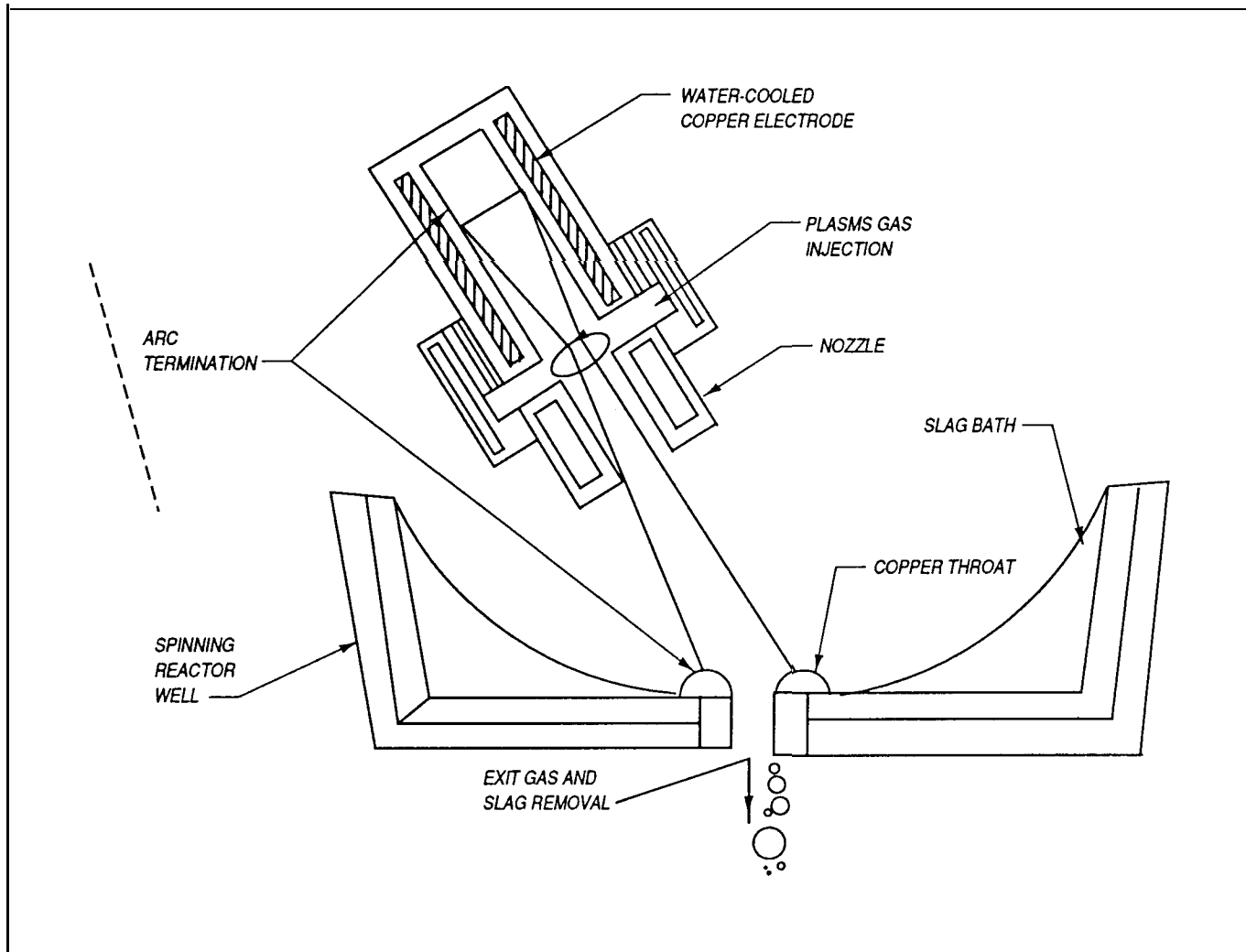
Figure 8-21. Schematic of the demonstration PCR showing the bottom-pour configuration for exit gas and molten glass (Source: EPA 1992a)

consumption and corresponding costs. Arcing resulting from induced currents in metallic components of waste may damage the microwave generator unless special provisions are made. Microwave technology has been used in Japan as a treatment process for a number of wastes and is being developed in America by Oak Ridge National Lab, Sandia National Lab, and the Rocky Flats Plant .

(12) Resistance heating. Initial large-scale testing of vitrification for high-level waste was done in crucibles heated by external resistance heaters. Crucible heating has the distinct disadvantages of low melt rates caused by slow heat transfer and lack of agitation and of temperature nonuniformities that make it difficult to homogenize the glass.

(13) Induction heating. Currently, induction heating application to hazardous and radioactive wastes is represented by the French AVM process (Atelier de Vitrification Marcoule). However, because induction heating is also used in commercial glass manufacturing, it is potentially applicable to radioactive wastes. Induction heating is accomplished by inducing currents in the material to be heated. For example, a solenoid can be used to create a variable magnetic field inside the coil and around it. If an electrically conductive body is placed inside the magnetic field, the variation in the magnetic field causes a variation in the magnetic flux passing through the material and induces an electromotive force (EMF) current. The EMF current causes eddy currents, and these are converted into heat due to the Joule effect.
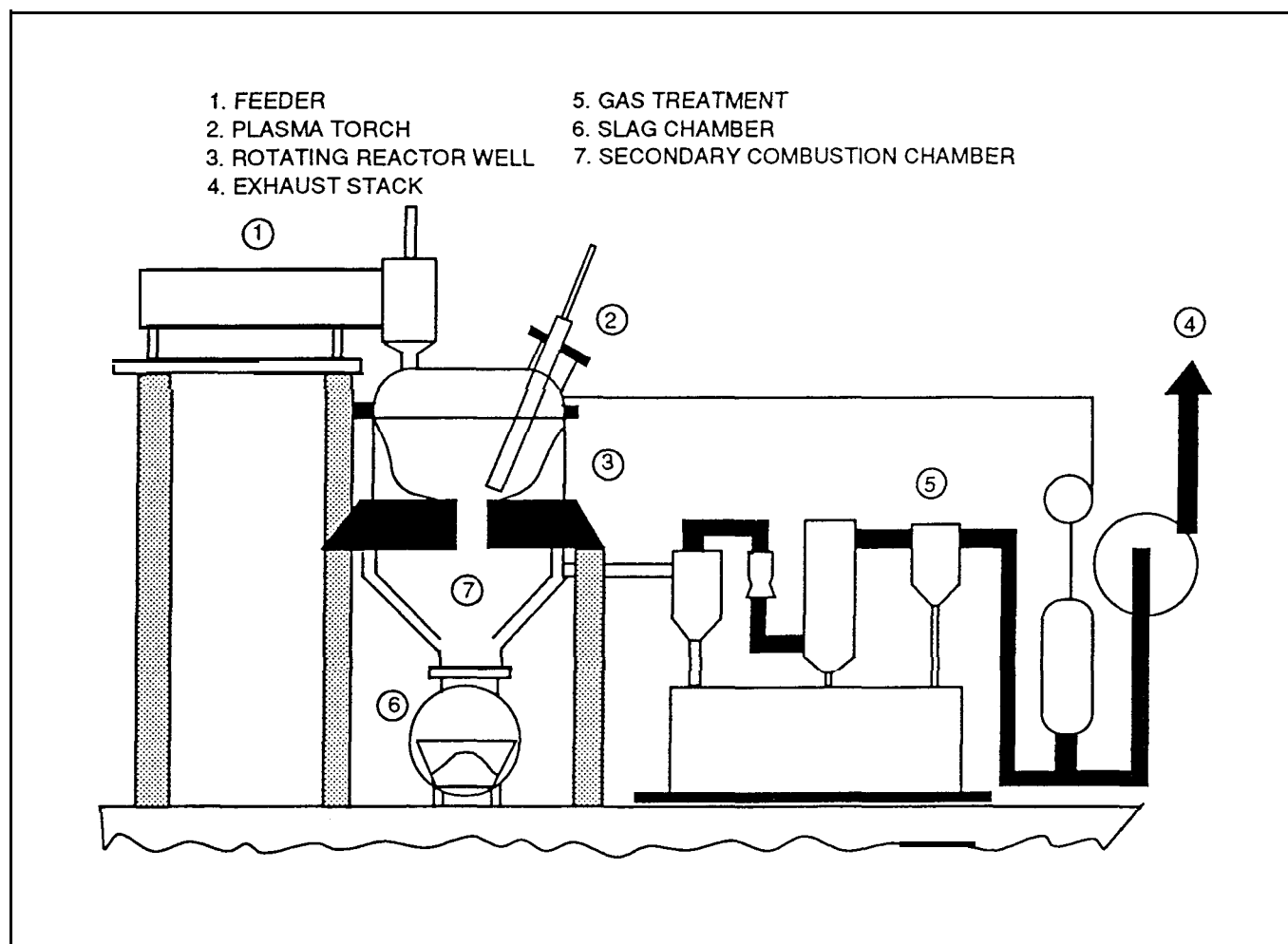
1. FEEDER   5. GAS TREATMENT
2. PLASMA TORCH   6. SLAG CHAMBER
3. ROTATING REACTOR WELL   7. SECONDARY COMBUSTION CHAMBER
4. EXHAUST STACK

Figure 8-22. Schematic of a full-scale PCR [Source: EPA 1992a)

(14) Electric arc furnaces. Electric arc furnaces heat by creating current flow between two electrodes in an ionized gas environment. They differ from plasma furnaces in that a plasma is not created and therefore not part of the heat transfer mechanism. The electric arc furnace was first developed in the metal industry. An electric arc process is being used by Electro-Pyrolysis, Inc., and the Massachusetts Institute of Technology to pyrolyze solid hazardous materials. It is also being used in vitrification tests in Albany, OR, of municipal solid waste bottom ash, fly ash, and the ash from sludge incineration. The Japanese are also working on electric-arc vitrification.

(15) Incineration/vitrification processes. Kiln incineration may be used as a vitrification process by itself or prior to a vitrification step in a treatment train. Vitrification is ideal for immobilizing the ash that is produced from incineration. In addition, rotary kiln incinerators

operated in the slagging mode may produce a vitrified product. At high enough temperatures, the material in the kiln will deform, producing an amorphous state in that material. This molten slag can then be tapped and may harden into a glass or glass-like product upon cooling, based on material composition. Leachability tests were conducted on the hardened slag produced in a 50,000-metric-ton/year rotary kiln operating at Rijnmond, Holland. Results indicated that the slag, as produced, would pass the EPA Toxicity Characteristics Leaching Procedure (TCLP) tests.

(16) Advantages and Disadvantages. Advantages and disadvantages of vitrification are presented in Table 8-22. A more detailed discussion is given in the following paragraphs.

(17) Advantages of vitrification. Potential capabilities and advantages of vitrification include:

Table 8-22
Advantages and Disadvantages of Vitrification

Advantages	Disadvantages
Organics are thermally destructed	Combustibles may generate gases
Reduced leachability of inorganic	Halogenated compounds affect product durability
Excellent long-term durability	Reducing agents cause problems
Offers treatment of a wide range of waste streams	Certain metals may cause quality or volatility problems
Can immobilize concentrated end products	Costly off-gas treatment system needed
Applies to both organics and inorganic	Shorting of electrodes is possible
Volume reduction	High cost of energy
Waste glass may be reused	Depth limitations
ISV offers reduction in worker safety and costs	Radiation shielding may be needed

(a) Organics may be thermally destructed by pyrolysis and combustion during vitrification.

(b) Waste glasses of many types have shown reduced leachability of inorganic.

(c) Long-term durability indicates a product that reduces leaching for long periods of time. It is possible to have a material that currently reduces leaching but that may not perform well over many years. Although not measured directly, the long-term durability of waste glass appears to be excellent and may extend to geologic time periods, as indicated by natural glass systems that have been stable for millions of years.

(d) A wide range of waste streams can be treated by vitrification without compromising the integrity of the final product.

(e) Vitrification can immobilize concentrated end products from other treatment processes such as incineration and precipitation.

(f) Because vitrification is both a high temperature process and an immobilization process, it can apply to both organics (thermal destruction) and inorganic

(immobilization). Vitrification may, therefore, be preferred at sites that present a complex mixture of hazardous and/or radioactive contaminants.

(g) During vitrification, volume of the incoming waste is generally reduced while density increases. This reduction in volume is the result of the vaporization of void gases, the vaporization of water in the feed, and the combustion of organic materials present in the feed. Volume reductions include 25-45 percent for ISV; 70-80 percent for glass melter vitrification of incinerator ashes; and 98-99.5 percent for microwave melter vitrification of liquid and sludge wastes. Obviously, volume reduction values vary widely with waste feed. Volume reduction during an ISV melt results in a depression at the treatment site which may be filled with clean soil or other fill. Density of vitrified products ranges from 2.3 to 3.0 g/cm^3, well above the densities of O.7 to 2.2 g/cm^3 measured for stabilized/solidified products.

(h) Vitrified waste glass may potentially be reused in various ways. Reuse may depend upon whether the product can be delisted according to EPA regulations.

(i) The avoidance of excavation, processing, and reburial of the product applies only to ISV and is important in two respects: worker safety and costs. Worker safety and costs are both reduced because the material is left in place.

The first five of these capabilities (a-e) are the direct result of the product. Capabilities f and g are the result of the flexibility of glass and the high temperatures under which vitrification is conducted. The last two capabilities are highly site-specific and will depend on site characteristics and treatment objectives.

(18) Disadvantages of vitrification. Disadvantages of the vitrification of waste materials include:

(a) Combustible materials generate gases which may carry contaminants to the glass surface and away from the melt. Pre-treatment processes can control combustibles in ex situ vitrification; however, combustibles must be controlled by processing conditions in ISV.

(b) Halogenated compounds affect product durability because incorporation into the glass in high enough concentrations may produce an undesirable, porous product.

(c) Reducing agents such as carbon and ferrous salts may reduce arsenates and selenates to lower valence

compounds that are more volatile and thus reduce incorporation efficiencies of these metals.

(d) Certain metals such as mercury and cadmium may be undesirable because of their difficulty to incorporate into the melt, their reduction of product quality, and/or because their volatility requires treatment in the off-gas system.

(e) An elaborate and costly off-gas treatment system is required because of the potential volatilization of contaminants.

(f) In joule heating, metals in the feed may cause shorting of the electrodes. The metals may sink to the bottom of the melt, concentrate there, and possibly create a conduction path that may lead to electrical shorting between the electrodes.

(g) The high cost of energy is a significant disadvantage to vitrification because the process requires large amounts of energy. A primary way in which vitrification can be used efficiently is at highly contaminated sites where the contamination is not diluted. Another factor that drives up cost is the high cost of trained operators.

(h) At present, depth limitations are a serious handicap to ISV. Currently, PNL has achieved a depth of 5 m and Geosafe has achieved a depth of 5.8 m. Sixty percent of DoD contaminated soil sites extend deeper than 5 m. If ISV could be extended to 9 m, then 90 percent of DoD sites would fall within ISV depths.

(i) Gamma radiation must be guarded against by shielding and remote operation. Beta radiation is

absorbed in the glass except from the surface layer, and alpha radiation is completely absorbed in the glass.

(19) Costs. Table 8-23 includes cost estimates ($/ton) provided by Geosafe Corporation and are for radioactive waste only. For mixed waste, add $70 to $120 to each estimate. These figures do not include transportation costs. The EPA handbook estimates equipment mobilization and demobilization costs at $50,000 plus $50 per transport mile. Treatability testing costs must also be included and are estimated to range from $40,000 to $70,000 or more. The costs involved in vitrification are discussed in more detail in the EPA handbook (EPA 1992) .

Table 8-23
Cost Estimates

Treatment Process	Estimated Cost, $/ton	$/kg
Landfilling:		
Onsite	240-390	0.27-0.44
Off site	230-450	0.26-0.51
Chemical Stabilization:		
Onsite	215-485	0.24-0.54
Off site	200-490	0.22-0.55
Incineration:		
Onsite	370-1,310	0.41-1.47
Offsite	675-2,470	0.76-2.77
Vitrification:		
In situ	450-650	0.51-0.73
Staged	490-800	0.55-0.90

compounds that are more volatile and thus reduce incorporation efficiencies of these metals.

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